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Novel edible coating based on Macadamia Nut oil and chitosan to maintain the antioxidant and physical properties of tomato fruits

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ABSTRACT

Innovative approaches for extending the shelf life of tomatoes are required due to increased postharvest losses of climacteric-fruits. The use of edible coatings is recently considered as a promising approach due to their non-toxicity and affordability properties. The coatings form physical barriers that alter the internal atmosphere of the fruit and slow down a ripening process. The influence of an edible coating comprising of chitosan and macadamia nut oil on the antioxidant and physical properties of tomato fruits is reported. The antioxidant and physical qualities of tomato fruits were investigated using different coating solutions. Various concentrations of macadamia nut oil, ranging from 1 % to 2.5 %, were used as independent coating solutions. Additionally, another set of coating solutions was prepared by mixing macadamia nut oil in the same concentration range (1 % to 2.5 %) with 1 % w/v chitosan. The tomatoes were dipped into the coating solutions and stored under a post-harvest shed (23.8–30 °C, 65.8–97.5 % RH) for 20 days to monitor total phenolic content, total flavonoid content, ascorbic acid content, color, percentage weight loss, decay percentage, and shelf life after every 5-days interval. The results showed a significant difference ($P < 0.05$) between coated and uncoated tomato samples. The coated tomatoes showed the significant retention of total flavonoid content, total phenolic content, hue angle and red-green (a*) compared to uncoated tomatoes. On contrast, the decrease of decay, weight loss, the lightness (L), blue-yellow (b*), chroma, and ascorbic acid content was lower for coated compared to control tomatoes. The findings indicated that 1 % macadamia nut oil exhibited the highest retention of antioxidant and physical properties, and lowest decrease in ascorbic acid content from 0.014 mg/100 g on the 5th day to 0.0096 mg/100 g on the 20th day was observed. Thus, the findings from this study suggest that the macadamia nuts can serve as a cheap and low-cost source of edible oil suitable for prolonging the shelf life of tomatoes and related fruits.

1. Introduction

Tomatoes (*Solanum lycopersicum*) are one of the most widely consumed and economically significant fruits due to their nutritional value, taste, and versatility in cooking applications (Ilahy et al., 2018; Yadav, Kumar, Upadhyay, Sethi & Singh, 2022). It is a second horticultural crop cultivated in Tanzania and it is estimated that about 51 % of farmers produce tomatoes (Sawe, Nielsen & Eldegard, 2020). Tomatoes is a good source of antioxidant compounds including phenolic compounds, flavonoid compounds, lycopene, and ascorbic acid among others. Phenolic compounds can inhibit enzymes associated with the development of human diseases and have been used to control various common human ailments, including hypertension, metabolic problems, inflammatory infections, and neurodegenerative diseases (Rahman et al., 2021). Dietary intake of flavonoid-rich foods is also associated with a reduced risk of some cancers (lung, colorectal, gastric) and with a low incidence of coronary heart disease (Janabi et al., 2020). Ascorbic acid is important in the formation and repair of bones, teeth, and collagen, which is the body's major building protein Trifunschi, Zugravu, Munteanu, Borcan and Pogurschi (2022).

The tomatoes like other climacteric fruits face post-harvest losses, resulting in a comparatively shorter postharvest shelf life. The losses are likely result of ethylene production, transpiration, and senescence that occur later in the harvesting process (Lufu, Ambaw & Opara, 2020). Additionally, the post-harvest quality deterioration in terms of phenolic content, flavonoid, ascorbic acid, and other organoleptic parameters like

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color and texture has been a challenge at the national and individual levels. Oxidative processes that degrade perishable tomato fruits are a major source of concern, as they not only result in financial losses but also qualities losses (Fernandez, Alves, Gaspar & Lima, 2021) (Lufu et al., 2020). Consequently, several preservative techniques including the use of modified atmosphere (MA) and controlled atmosphere (CA) to prolong the shelf life of fruits have been developed (Kargwal, Garg, Singh, Garg & Kumar, 2020). However, most of the techniques are expensive and induce the hypoxia condition in tomato cells that triggers the anaerobic respiration of pyruvate to ethanol and carbon dioxide (Brizzolara, Manganaris, Fotopoulos, Watkins & Tonutti, 2020). Thus, the development of preservative techniques that are cheap and do not induce quality deterioration of tomatoes are highly required.

Edible coatings are a promising innovation in preserving fruits and vegetables because are naturally available, less expensive, and environmentally friendly (Al-Tayyar, Youssef & Al-Hindi, 2020). Previous studies have demonstrated the use of edible coating materials such as chitosan and *Aloe vera* gel (Yoshida et al., 2021) (Hesami, Kavoosi, Khademi & Sarikhani, 2021), *Citrus sinensis* essential oil (Manzur et al., 2023), *Azadirachta indica* (Zewdie, Shonte & Woldetsadik, 2022), *Opuntia oligocantha*, and *Vitis vinifera* (Aloui et al., 2014), which efficiently extend the shelf life and maintain the quality of tomatoes. The edible coatings are reported to trigger the synthesis of antioxidants phytochemicals such as flavonoid, and phenolic compounds prompted by various intracellular signals including increased ROS concentration, activation of membrane G-proteins, or cytosol acidification (Meitha, Pramesti & Suhandono, 2020; Tomazeli et al., 2016). The phytochemicals increase an antioxidant defense system by scavenges the reactive oxygen species (ROS) that are destructive to the quality of fruits. The coatings also activate antioxidant enzymes such as superoxide dismutase (SOD), catalase enzyme (CAT), ascorbate peroxidase (APX)) and other metabolic enzymes (phenylalanine ammonia-lyase (PAL) and lysyl oxidase (LOX)) that prolong the shelf life of fruits.

The macadamia nuts are a rich source of monounsaturated fats that contribute to heart health, along with essential nutrients like vitamin E, magnesium, and antioxidants (Kaseke, Fawole & Opara, 2021). The macadamia nut oil extracted from the nuts contains fatty acids with antibacterial and antioxidant properties (Maestri, Cittadini, Bodoira & Martínez, 2020). Consequently, the fatty acids in macadamia nut oil are promising components for edible coatings suitable for the preservation of fruits (Wani et al., 2017). The compounds can form a semi permeable layer that prevents fruits against microbial attacks due antimicrobial properties. Additionally, the layer can inhibit the fruits deterioration caused by ROS due its antioxidant properties and extend the shelf life of fruits. However, the information on the use of the oil in the edible coatings for extension of shelf life of fruits is still limited. Therefore, the potential of macadamia nut oil and chitosan as a natural source of compounds for the preservation of tomato fruits was investigated in the current study. Chitosan was used to increase the hydrophobic and electrostatic interactions caused by its N-acetylated residues (Ardean et al., 2021). The findings from this study will not only contribute to expanding the knowledge of natural food preservation techniques but also provide insights for the food industry in developing sustainable and healthier alternatives.

2. Materials and methods

2.1. Materials

Fresh tomato fruits (*Lycopersicon esculentum Mill.*), variety Assila F1, were freshly harvested from a farm, and carefully transported to avoid mechanical damage. The tomatoes selected for experiments were homogeneous in the ripening stage, free from mechanical damage, blemishes, and fungal attacks. The other materials used in experiments include an oven, blender (Mister Chef® 2200 W), ultrasonic bath (Branson Ultrasonics, Emerson Japan), UV–visible spectrophotometer (Double beam UV-3000 model X-ma 3000 spectrophotometer, Human Corporation, England), chroma meter, analytical balance (BYY 21, Germany), rotary vacuum evaporator, Whatman No. 2 filter paper. Chemicals used including petroleum ether, potassium acetate, Potassium Iodide (KI), Sodium carbonate (Na_2CO_3), gallic acid, vitamin C, Dimethyl Sulfoxide (DMSO), catechin and Aluminum Chloride ($AlCl_3$) were of standard analytical grades.

2.2. Preparation of macadamia nuts oil

The macadamia oil was prepared using freshly harvested macadamia nuts collected from the horticultural unit at the Sokoine University of Agriculture, Tanzania. The collected nuts were cleaned using distilled water and sun-dried for seven (7) days. Husks were removed from the dried fruits and collected kernels grinded into powder using the blender. The oil from the macadamia nut powder was extracted at 80 °C for 7 hours using the soxhlet extraction method (Navarro & Rodrigues, 2016; Shuai et al., 2022). Briefly, the nut powder (46 g) was placed into thimbles attached to a round-bottomed flask containing petroleum ether (250 mL) in a water bath. After the extraction, the solvent was removed using a rotary evaporator (BUCHI Rotavapor R-205). The collected macadamia oil was stored in freezer at 4 °C

2.3. Preparations of coating formulations

The coating formulations (Table 1) were prepared using varying concentrations of macadamia nut oil ranging from 1 % v/v to 2.5 % v/v. These formulations involved the addition of specific chemicals, including 1 %w/v calcium chloride as a crosslinking agent, 2 %w/v ascorbic acid as an antioxidant, 3 %w/v carboxyl methyl cellulose (CMC) as a thickener, and 2 % v/v glycerol to prevent precipitation. In this study, 1 %w/v chitosan was also added to the coating solution to form the other formulations, such as 1 % macadamia nut oil with 1 %w/v chitosan (S2), 2 % v/v macadamia nut oil with 1 %w/v chitosan (S3), and 2.5 % v/v macadamia nut oil with 1 % chitosan (S4). Chitosan (1 % (w/v)) solution was prepared by dissolving 1 g of chitosan pellets into 1 % (v/v) acetic acid to provide a total volume of 100 mL. The acetic acid (1 %) used so as to protonate the chitosan, therefore it solubilize into acqueous medium (Giraldo & Rivas, 2021) (Rinaudo, Pavlov & Desbrières, 1999). Then, this mixture was stirred for 45 min using an ultrasonicator (probe-type with 50 to 400 W) until a completely transparent solution was achieved and added to macadamia nut oil. Subsequently, the resulting coating solution was pasteurized using an intelligent water batch (MODEL-WB-15) fixed to 75 °C for 15 min to eliminate any germs present in the solution. The study employed a completely randomized design (CRD) with seven treatments and two replications. The experiments were conducted in a postharvest shed for 20 days of storage.

2.4. Application of coatings formulation on tomatoes

The tomatoes were washed with distilled water to remove dust residues. The samples were then sprayed with 70 % ethanol to kill germs and dried for 15 min at room temperature (23.8–30 °C). The coating solutions were applied to tomato surfaces using a dipping method. One group of tomatoes termed control samples were immersed in distilled water and then air-dried for 60 min. Qualities of tomatoes, such as total phenolic content, total flavonoid contents, ascorbic contents, color, decay percentage, and shelf life were analyzed for 20 days at 5-day interval. Tomatoes were divided into seven groups, including control, 1 % v/v macadamia nut oil with 1 %w/v chitosan (S2), 2 % v/v macadamia nut oil with 1 %w/v chitosan (S3), 2.5 % v/v macadamia nut oil with 1 %w/v chitosan (S4), and macadamia nut oil (1 % v/v (S5), 2 % v/v (S6), and 2.5 % v/v (S7). After coatings, tomatoes were air-dried for 60 min at ambient temperature (23.8–30 °C). Both coated and control were stored in a postharvest shed with conditions of 23.8–30 °C, 65.8–97.5 % RH

Table 1
Showing the coating solutions where (S1= control, S2=1 % v/v macadamia nut oil +1 % w/v chitosan, S3=2 % v/v macadamia nut oil +1 %w/v chitosan and S4= 2.5 % v/v macadamia nut oil +1 %w/v chitosan, S5=1 % v/v macadamia nut oil, S6=2 % v/v macadamia nut oil and S7= 2.5 % v/v macadamia nut oil.

Macadamia nut oil (% v/v)	Chitosan (% w/v)	Additives				Coating formulations
		Calcium chloride (% w/v)	Carboxyl methyl Cellulose (% w/v)	Glycerine (% v/v)	Ascorbic acid (% w/v)	
0	0	0	0	0	0	S1
1	1	1	3	2	2	S2
2	1	1	3	2	2	S3
2.5	1	1	3	2	2	S4
1	0	1	3	2	2	S5
2	0	1	3	2	2	S6
2.5	0	1	3	2	2	S7

2.5. Physiological loss in weight (%)

The weight of tomatoes was measured an analytical balance as reported elsewhere (Firdous, Khan, Butt & Shahid, 2020). The physiological loss in weight (PLW) was estimated at an interval of 5 days during storage for 20 days. Initial tomato and final weights were recorded at the beginning and end of the storage period, respectively. The tomatoes were weighed after every five storage days. The PLW for each date of observation was calculated using Eq. (1).

$$\text{Physiological loss in weight (\%)} = (\text{Initial Weight} - \text{Final weight})\text{g}/\text{Initial Weight (g)} * 100 \quad (1)$$

2.6. Color

Color of tomatoes from each batch were inspected using Chroma meter (Firdous et al., 2020) and the values of L, a, b, Chroma meter, and hue angle were recorded.

2.7. Determination of total phenolic content and total flavonoid content

The phenolic and flavonoid contents were determined as previously described (Alenazi et al., 2020). Briefly, tomato fruits were crushed and ground into fine paste using the blender. The resultant tomato paste (2 g) was extracted with a 25 mL of 80 % (v/v) methanol mixture in ultrasonic bath for 1.5 min. The mixture was filtered using Whatman No. 2 filter paper, and the filtrate dried using a rotary vacuum evaporator. Dried samples were stored at −20 °C until further analysis.

2.7.1. Determination of total flavonoid content

Total flavonoid content of extracts was determined using the colorimetric method with minor modifications (Shraim, Ahmed, Rahman & Hijji, 2021). Briefly, 0.5 mL of extracts were combined with 5 mL of aluminum chloride solution (10 %), followed by the addition of 5 mL potassium acetate (1 M) with 3 mL of distilled water. A reaction mixture was incubated at room temperature for 30-minutes and its absorbance measured by a UV–Visible Spectrophotometer at 510 nm against the reagent as a blank. The calibration curve was plotted using 20–500 µg/mL of catechin as a standard, and total flavonoid content was expressed as mg of catechin equivalent per gram of extract (mg CE/g extract).

2.7.2. Determination of total phenolic content

Total phenolic content of the extracts was determined by Folin-Ciocalteu method with minor modifications (Katırcı et al., 2020). In brief, 2 mL of extracts were mixed with 0.5 mL of Folin-Ciocalteau reagent, followed by incubation at room temperature for 5 min. The reaction mixture was then incubated at room temperature for 1.5 h in dark after the addition of 1.5 mL sodium carbonate solution (7.5 %). Next, absorbance of the samples was recorded at 725 nm against reagent as blank using UV–Visible Spectrophotometer (Double beam UV-3000 model X-ma3000 spectrophotometer Human Corporation, England). Gallic acid was used as standard and calibration curve was prepared at concentration ranges from 20 to 500 µg GA/mL. The total phenolic content was expressed as mg gallic acid equivalents per gram extract (mg GAE/g extract).

2.8. Determination of ascorbic acid (Vitamin C)

Ascorbic acid was determined by redox titration using iodine solution of 0.01 M (Samayoa-Oviedo & Laskin, 2022), in which 5 g of blended fresh tomato sample was placed in conical flask, then distilled water was added up to the 50 mL mark, the sample solution was homogenized, filtered and titrated with 0.01 M iodine solution by using 1 % starch as indicator until the blue-black color observed, the same procedure was done for standard solution of vitamin C. Then ascorbic acid content was determined using Eq. (2).

$$\text{Ascorbic acid g} / 100 \text{ g of sample} = \text{Cstd} \times \text{VIs} \times \text{Vext x } 100/\text{VIst x Vs} \times \text{Wt} \quad (2)$$

Where, *Cstd* = Concentration of standard ascorbic acid in g/mL
VIs = Volume used of iodine in sample titration.
Vext = Extraction volume/ total volume of sample solution
VIst = Volume used of iodine in standard vitamin C titration
Vs = Volume of sample taken for titration
Wt = Weight/ volume of sample used
100 = conversion factor per 100 g

2.9. Decay percentage

Decay or rotting of tomatoes was determined through the visual observation (Moneruzzaman, Hossain, Sani, Saifuddin & Alenazi, 2009).

Briefly, The development of spots on the fruit, softening, and rotting of the fruits were recorded based on the method described in a previous study.

2.10. Shelf life

The determination of tomato fruit shelf life, involved calculating the duration during which the tomatoes remained free from spoilage. This assessment was conducted by tracking the progression of each treatment group and recording the number of days until visible signs of deterioration appeared. Factors such as changes in color were closely monitored to ascertain the efficacy of the different formulations of macadamia nut oils, and chitosan in preserving the quality and extending the shelf life of the tomatoes (Sinha et al., 2019).

2.11. Data analysis

The independent variables used in study were coating solutions and storage time while dependent variables were total phenolic content, total flavonoid content, ascorbic acid content, physiological weight loss, color, and decay percentages. The data were tested for normality and homogeneity using Kolmogorov-Smirnov-test and the Shapiro test, to determine the parametric and non-parametric test. Results indicated that all data exhibited normal distribution (KS value > 0.05. Due to the presence of two categorical independent variables, data were subjected to two-way analysis of variance (ANOVA) on SPSS version 25 at ($P \leq 0.05$). These analyses revealed statistically significant differences across all parameters. Consequently, post hoc analysis employing the least significant difference (LSD) was employed to identify formulations with significant differences from each other.

3. Results

3.1. Total phenolic content (TPC)

The findings (Fig. 1) demonstrated a significant effect ($P \leq 0.05$) of the composite solution of macadamia nut oil and chitosan on changes in total phenolic content (TPC). Initially, both control and coated samples exhibited increased TPC over the 20-day storage period. However, the increase in TPC for the uncoated group of tomatoes was higher than the coated group, reaching 150 mg GAE/100 g on the 20th day of storage (Fig 1). Among the coating formulations, S5 (1 % v/v macadamia nut oil + 1 %w/v chitosan) showed the smallest increase in TPC. The significance difference ($P \leq 0.05$) in TPC was observed between S5 and S4 formulations and insignificant changes in TPC ($P > 0.05$ were noted for treatments with S2, S3, S6, and S7. The findings suggest that the optimal TPC values were achieved in tomato samples coated with S5, which is within ranges reported by other scholars (Kumar, Neeraj, Pratibha & Trajkovska Petkoska, 2021).

3.2. Total flavonoid content (TFC)

The results in Fig. 2 indicate that different formulations of coating solutions comprising macadamia nut oil and chitosan had a significant effect ($P \leq 0.05$) on the changes in total flavonoid content (TFC) across all samples. Generally, the TFC increased throughout tomatoes' storage life and ripening. However, the increase in total flavonoid content for coated was lower compared to non-coated samples. The initial total flavonoid content for uncoated tomatoes was 0.105 mg/100 g, which increased throughout the storage life until it reached 0.47 mg/100 g. Meanwhile, the coating formulation of 1 %macadamia nut oil (S5) produced a TFC content of 0.19 mg/100 g on the 20th day. Apart from S5, formulations that maintained the flavonoid content of tomatoes within the acceptable range up to 20 days were S2 (0.165 mg/100 g) and S4 (0.225 mg/100 g) on the 20th storage day. The observations suggest that the coating formulations S5 offered the best preservation effect by reducing the degradation of flavonoid content.

3.3. Physiological weight loss

The effect of macadamia nut oil and chitosan formulations on the weight loss of tomato fruits is depicted in Fig. 3. The results indicate that weight loss increased with storage time for all samples. The increase in weight loss was significantly higher ($P < 0.05$) for the control samples, with values of 2.8 %, 7.2 %, 8.7 %, and 10.34 % on the 5th, 10th, 15th, and 20th days of storage, respectively. Among the coated tomato samples, the lowest percentage weight loss was recorded for the S5 formulation, indicating values of 2.03 %, 4.12 %, 5.12 %, and 6.03 % on the

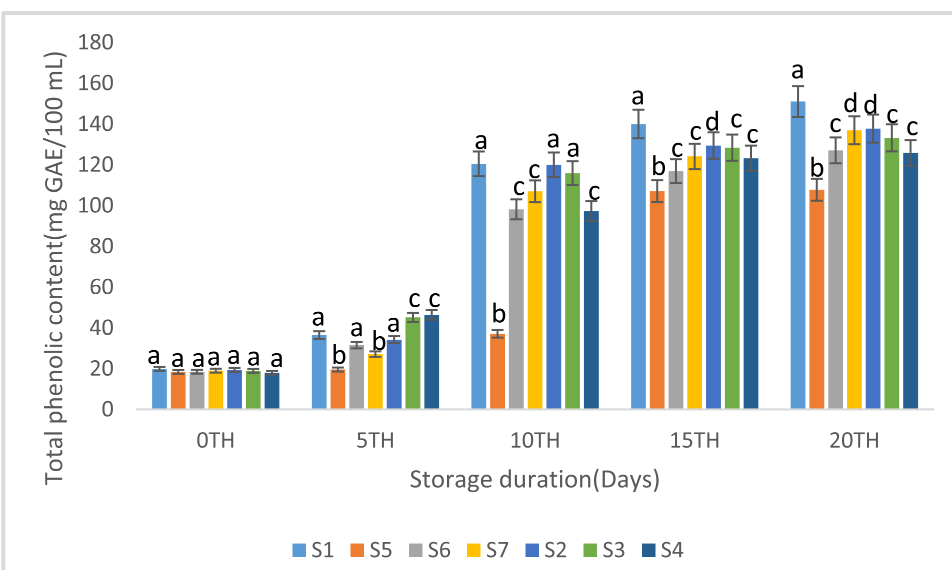

Fig. 1. Changes in total phenolic content of tomato fruits stored at the postharvest shed. Where by (S1= control, S2=1 % v/v macadamia nut oil +1 % w/v chitosan, S3=2 % v/v macadamia nut oil +1 % w/v chitosan and S4= 2.5 % v/v macadamia nut oil +1 % w/v chitosan, S5=1 % v/v macadamia nut oil, S6=2 % v/v macadamia nut oil and S7= 2.5 % v/v macadamia nut oil). Each value represents the mean of two biological replicates ± standard error bar. The mean followed by the different letters are significantly different ($P \leq 0.05$).

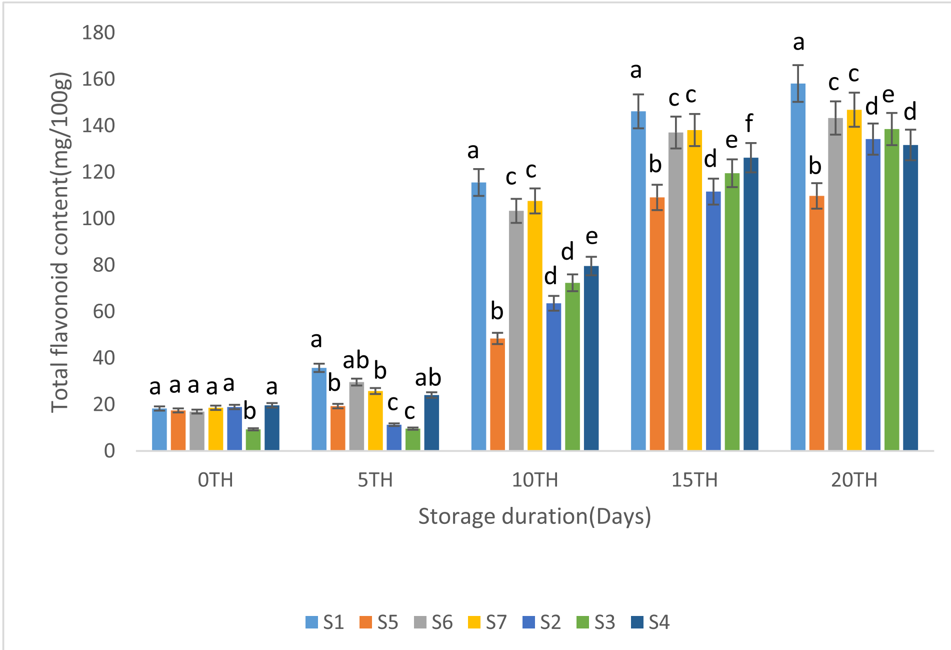

Fig. 2. Changes in total flavonoid content of tomato fruits stored at the postharvest shed. Where by (S1= control, S2=1 % v/v macadamia nut oil +1 % w/v chitosan, S3=2 % v/v macadamia nut oil +1 % w/v chitosan and S4= 2.5 % v/v macadamia nut oil +1 % w/v chitosan, S5=1 % v/v macadamia nut oil, S6=2 % v/v macadamia nut oil and S7= 2.5 % v/v macadamia nut oil). Each value represents the mean of two biological replicates ± standard error bar. The mean followed by the different letters are significantly different ($P \leq 0.05$).

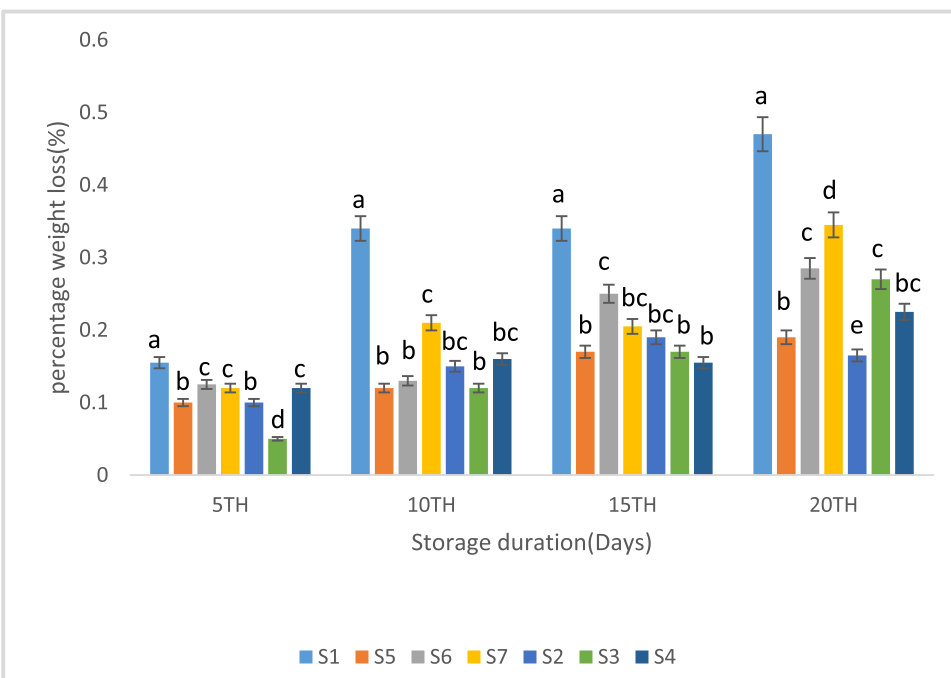

Fig. 3. Changes in physiological weight loss of tomatoes fruits stored at postharvest shed. Where by (S1= control, S2=1 % v/v macadamia nut oil +1 % w/v chitosan, S3=2 % v/v macadamia nut oil +1 % w/v chitosan and S4= 2.5 % v/v macadamia nut oil +1 % w/v chitosan, S5=1 % v/v macadamia nut oil, S6=2 % v/v macadamia nut oil and S7= 2.5 % v/v macadamia nut oil). Each value represents the mean of two biological replicates ± standard error bar. The mean followed by the different letters are significantly different ($P \leq 0.05$).

5th, 10th, 15th, and 20th storage days, respectively. Moreover, S4 showed significantly lower percentage weight loss compared to the control sample, with values observed at 2.83 %, 3.92 %, 6.42 %, and 7.74 % on the 5th, 10th, 15th, and 20th days, respectively. These observations indicate that the presence of the edible coating formulations effectively reduced weight loss in tomato fruits.

3.4. *Ascorbic acid levels*

In this study, the concentration of ascorbic acid in tomato fruits was

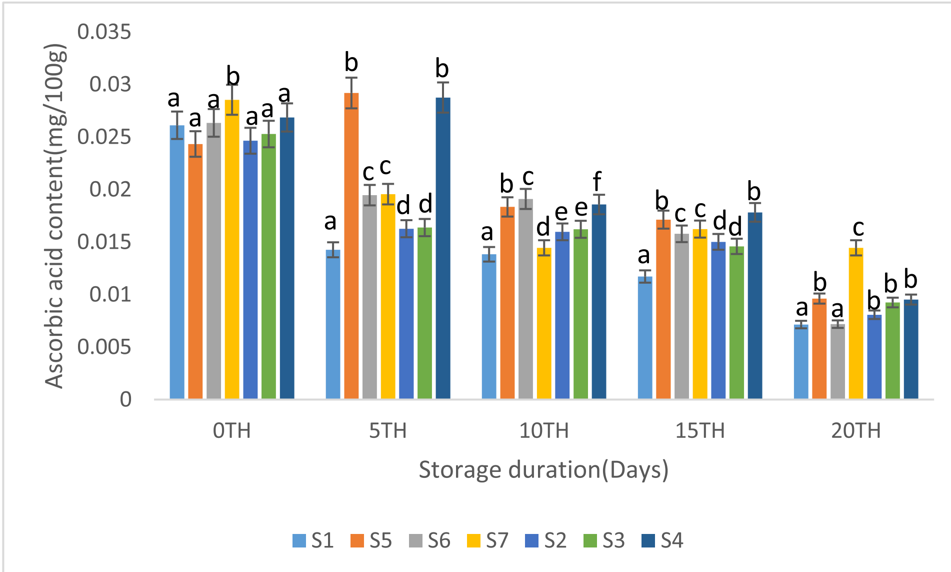

Fig. 4. Changes in ascorbic acid content of tomatoes fruits stored at postharvest shed. Where by (S1= control, S2=1 % v/v macadamia nut oil +1 % w/v chitosan, S3=2 % v/v macadamia nut oil +1 % w/v chitosan and S4= 2.5 % v/v macadamia nut oil +1 % w/v chitosan, S5=1 % v/v macadamia nut oil, S6=2 % v/v macadamia nut oil and S7= 2.5 % v/v macadamia nut oil). Each value represents the mean of two biological replicates ± standard error bar. **The** mean followed by the different letters are significantly different ($P \le 0.05$).

measured to evaluate the effectiveness of the applied coating. The findings (Fig. 4) revealed that the concentration of ascorbic acid in tomato fruits decreased over time during storage. Specifically, tomato fruits treated with the S5 formulation (1 % macadamia nut oil) exhibited ascorbic acid contents of approximately 0.020 mg/100 g, 0.018 mg/100 g, and 0.016 mg/100 g on the 5th, 10th, and 15th days, respectively.

Table 2
Effect of macadamia nut oil and chitosan formulations on L, a*, b*, Chroma, and hue angle of tomatoes stored postharvest shed on 20 storage duration. Values followed by the same letter in each column for each day do not differ significantly ($P < 0.05$). Where by (S1= control, S2=1 % v/v macadamia nut oil +1 % w/v chitosan, S3=2 % v/v macadamia nut oil +1 % w/v chitosan and S4= 2.5 % v/v macadamia nut oil +1 % w/v chitosan, S5=1 % v/v macadamia nut oil, S6=2 % v/v macadamia nut oil and S7= 2.5 % v/v macadamia nut oil).

Storage duration(days)	Treatment	L*	a*	b*	Chroma	Hue angle
0th	S1	58.817± 5.746	18.537 ± 1.660	20.737 ± 2.060	27.211 ± 2.480	.744 ± 0.060
	S2	59.427± 5.746	19.723 ± 1.660	21.173 ± 2.060	27.235 ± 2.480	.694 ± 0.060
	S3	57.321± 5.746	16.321 ± 1.660	20.184 ± 2.060	27.146 ± 2.480	.721 ± 0.060
	S4	58.271± 5.746	14.532 ± 1.660	19.163 ± 2.060	27.164 ± 2.480	.693 ± 0.060
	S5	55.534± 5.746	17.191 ± 1.660	21.237 ± 2.060	27.274 ± 2.480	.676 ± 0.060
	S6	55.993± 5.746	16.753 ± 1.660	21.423 ± 2.060	27.927 ± 2.480	.715 ± 0.060
	S7	59.432± 5.746	19.125 ± 1.660	19.772 ± 2.060	27.174 ± 2.480	.713 ± 0.060
5th	S1	46.475 ± 7.038a	25.390± 2.033a	17.390± 2.523a	30.774± 3.037a	.361 ± .074a
	S2	51.010 ± 7.038b	25.055± 2.033b	18.195 ± 2.523b	28.983±3.037a	.397± .074a
	S3	50.070 ± 7.038b	24.005± 2.033c	18.400 ± 2.523b	28.246 ± 3.037b	.428 ± .074b
	S4	52.130 ± 7.038c	27.635± 2.033d	18.935 ± 2.523c	28.526± 3.037c	.362 ± .074c
	S5	52.170 ± 7.038c	27.875± 2.033d	19.305 ± 2.523d	27.914± 3.037d	.366 ± .074c
	S6	48.675 ± 7.038d	26.825± 2.033e	17.915 ± 2.523e	29.258± 3.037e	.347± .074d
	S7	49.390 ± 7.038d	29.480± 2.033f	19.345 ± 2.523f	30.262± 3.037f	.337 ± .074e
10th	S1	44.495 ± 7.038a	27.295 ± 2.033a	15.180 ± 2.523a	31.242 ± 3.037a	.258 ±.074a
	S2	44.140 ± 7.038b	26.155±2.033b	16.210 ± 2.523b	30.783 ± 3.037b	.310 ± .074b
	S3	42.005 ± 7.038b	25.770±2.033c	16.260 ± 2.523b	30.471 ± 3.037b	.317 ± .074c
	S4	43.860 ± 7.03bc	29.855±2.033d	17.105 ± 2.523c	34.448 ± 3.037c	.271 ± .074c
	S5	46.700 ± 7.038d	28.705±2.033e	17.655± 2.523d	27.005 ± 3.037d	.304 ± .074b
	S6	41.975 ± 7.038e	30.025±2.033f	15.950 ± 2.523ae	34.006±3.037e	.240 ± .074d
	S7	41.040 ± 7.038f	30.225±2.033f	16.895 ± 2.523f	34.628± 3.037e	.260 ± .074e
15th	S1	30.465 ± 7.038a	28.040± 2.033a	7.540 ± 2.523a	29.078 ± 3.037a	.071 ± .074a
	S2	32.990 ± 7.038b	27.570± 2.033b	10.140 ± 2.523b	29.413 ± 3.037a	.125 ± .074a
	S3	33.960 ± 7.038b	27.640± 2.033b	12.375 ± 2.523c	30.294 ± 3.037b	.177± .074b
	S4	37.020 ± 7.038c	31.780± 2.033c	15.250 ± 2.523d	28.300 ± 3.037c	.200 ± .074c
	S5	39.720 ± 7.038d	29.555± 2.033d	15.830 ± 2.523e	27.538 ± 3.037d	.241 ± .074bc
	S6	32.115 ± 7.038e	31.280± 2.033f	13.370 ± 2.523f	29.054 ± 3.037e	.167 ± .074d
	S7	38.265 ± 7.038f	31.485± 2.033f	15.600 ± 2.523d	29.149 ± 3.037f	.212 ± .074d
20th	S1	23.410 ± 7.038a	28.985 ± 2.033a	5.715 ± 2.523a	29.554 ± 3.037a	.039 ± .074a
	S2	24.543 ± 7.038b	28.453 ± 2.033b	6.543 ± 2.523b	28.453 ± 3.037b	.413 ± .074b
	S3	26.438 ± 7.038b	28.99±2.033ab	8.435 ± 2.523c	29.12±3.037ab	.524 ± .074c
	S4	25.850 ± 7.038c	29.835 ± 2.033a	8.850 ± 2.523c	28.999 ± 3.037b	.786± .074d
	S5	31.495 ± 7.038d	30.595 ± 2.033b	12.815 ± 2.523d	28.004 ± 3.037c	.199± .074d
	S6	24.050 ± 7.038e	33.225 ± 2.033c	12.654 ± 2.523e	34.385 ± 3.037d	.068 ± 0.074 cd
	S7	24.040 ± 7.038e	30.535 ± 2.033b	12.650 ± 2.523e	32.713 ± 3.037e	.135 ± .074f

Conversely, the control group of tomatoes in the study displayed values of about 0.026 mg/100 g, 0.024 mg/100 g, 0.0138 mg/100 g, and 0.0137 mg/100 g on the 0th, 5th, 10th, and 15th storage days, respectively.

Thus, the S5 formulation exhibited the highest ascorbic acid content compared to other formulations as depicted in Fig. 3. The decrease in the ascorbic acid content was reported to be a possible result of the oxidation caused by ascorbic acid oxidase (Chatzopoulou et al., 2020).Thus, the presence of edible coating minimizes the direct contact of tomato skin with oxygen and prevents autoxidation responsible for the reduction in ascorbic acid content during ripening (Nicolau-Lapeña et al., 2021). Thus, edible coatings appear to be effective in retarding the degradation of ascorbic acid during storage.

3.5. Color changes

The findings regarding the color changes of tomatoes subjected to macadamia nut oil and chitosan formulation are presented in Table 2. The hue, chroma, L*, a*, and b* values clearly illustrate the differences in color between coated and uncoated tomatoes. L* indicates the degree of lightness and darkness (from white to black), a* displays the variation in red and green, and b* provides information about yellow and blue hues. The total color difference in a sample was represented by ΔE, which clearly demonstrates that as the storage life of the sample increased, the values of ΔE were highest for uncoated samples and gradually decreased for coated samples. Hue represents the difference between a specific color and a gray color of the same lightness. Chroma was defined as the amount of difference in hue compared to a gray color with equal lightness. Humans perceive objects more vividly when they have higher chroma values. Table 2 displays highly significant differences ($P < 0.05$) in the postharvest color parameters among the tomatoes stored under the postharvest shed. Up to 20th day of storage life, the L* value decreased for every sample. However, the S5 formulation showed a significant smallest decrease ($P < 0.05$) in the L* value compared to other formulations. At the end of storage, the values for S1, S2, S3, S4, S5, S6, and S7 samples were 23.410, 24.543, 26.438, 25.850, 31.495, 24.050, and 24.040 respectively. The non-coated sample showed a significantly higher decrease in lightness at the end of storage, whereas the 1 % macadamia nut oil (S5) showed a better L* value and better brightness. Over the 20th day of storage life, the b* (blue to yellow) values for both coated and uncoated samples progressively decreased. Despite the decreased value of b*, the tomato sample treated with S5 had lower dropped values as shown in Table 2, where the values at 0th, 5th, 10th, 15th, and 20th days were 20.737, 19.305, 17.655, 15.830, and 12.815 respectively. In contrast, the control sample had a higher decrease in b* values, where the values at 0th, 5th, 10th, 15th, and 20th storage days were 20.737, 17.390, 15.180, 7.540, and 5.715 respectively.

The production of carotenoid pigments is responsible for the decrease in the b* value (Kolašinac, Dajić-Stevanović, Kilibarda & Kostić, 2021). On the other hand, the value of a* increases with the respiration and ripening of tomato fruit. In the current study, the value of a* for the S3 formulation showed a slight increase compared to the control. Similarly, the coated guavas were showed the slightly increased in a* values (shown in red or green) that increased with storage life and were higher for the un-coated guavas (Yadav et al., 2022). The lower increases in a* values suggest that coatings performed better in retaining color. The S5 sample demonstrated superior chroma retention, as evidenced by the least significant ($p < 0.05$) decrease in color intensity observed in this coating compared to uncoated samples.

3.6. Decay percentages and shelf life

Edible coating formulations prepared from macadamia nut oil and chitosan successfully delayed the senescence and ripening of tomato fruits until the 20th days of storage (Table 3). The non- coated tomatoes exhibited more visible decay than fruits coated with macadamia nut oil and chitosan coatings during the storage period (Fig. 5). On 10th day, the higher rate of decay was reported to S1 (13.33 %) compared to S6 (6.7 %) and S7 (6.7 %). By the 10th day, S1 (13.33 %) exhibited a higher decay rate compared to S6 (6.7 %) and S7 (6.7 %). Among all coating formulations, S4 (2.5 % macadamia nut + 1 % chitosan) and S5 sustained the lowest decay percentage, maintaining freshness until the 20th day of storage. Notably, samples treated with S4 and S5 showed no observable decay until the 10th day, with their highest decay percentages reaching 26.7 % by the 20th day, representing the lowest decay percentage observed in this study (Table 3). Furthermore, considering decay percentages and percentage weight loss, the shelf life of tomatoes was determined. S4 and S5 exhibited a longer lifespan in storage compared to other treatments, with weight losses below 0.22 %, while the control experienced the highest weight loss percentage, reaching 0.47 % by the 20th storage day. Based on these parameters, the shelf life of tomatoes treated with S4 and S5 was determined to be 18 days.

4. Discussion

The deterioration of tomatoes is primarily influenced by factors such as respiration, transpiration, and ethylene production (Lima et al., 2022). The higher the respiration rate of tomatoes, the higher the degradation of biomolecules present in fruits, thereby reducing their qualities. Notably, tomatoes treated with the S5 formulation exhibited a significant reduction in respiration, transpiration, and ethylene production. Previous studies have shown that chitosan-based coatings can effectively reduce the respiration rate and ethylene production in tomatoes (Kumarihami et al., 2021). In this current study, the effects of macadamia nut oil, both alone and in combination with chitosan, were examined. Quality parameters such as total phenolic content, total flavonoid content, ascorbic acid content, decay percentages, and color were analyzed. The quality of coated tomatoes differed significantly from that of uncoated tomatoes, likely due to reduced metabolic reactions facilitated by decreased air permeability. Coatings cover pore spaces through which air can permeate, resulting in reduced gas diffusion, lower fruit respiration rates, and decreased transpiration rates, as previously described by other researchers' (Adhikary, Gill, Jawandha &

Table 3
Percentage decay of tomatoes under study and its corresponding shelf life. Where by (S1= control, S2=1 % v/v macadamia nut oil +1 % w/v chitosan, S3=2 % v/v macadamia nut oil +1 % w/v chitosan and S4= 2.5 % v/v macadamia nut oil +1 % w/v chitosan, S5=1 % v/v macadamia nut oil, S6=2 % v/v macadamia nut oil and S7= 2.5 % v/v macadamia nut oil).

Storage duration (days)	S1 (Control)	S2 (1 %v/v Macadamia Nut Oil + 1 %w/v Chitosan)	S3 (2 %v/v Macadamia Nut Oil + 1 %w/v Chitosan)	S4 (2.5 %v/v Macadamia Nut Oil + 1 %w/v Chitosan)	S5 (1 %v/v Macadamia Nut Oil)	S6 (2 %v/v Macadamia Nut Oil)	S7 (2.5 %v/v Macadamia Nut Oil)
0th	0	0	0	0	0	0	0
5th	6.7 %	0	0	0	0	0	0
10th	13.33 %	0	0	0	0	6.7 %	6.7 %
15th	33.33 %	26.7 %	26.7 %	13.33 %	13.33 %	26.7 %	46.7 %
20th	66.7 %	46.7 %	46.7 %	26.7 %	26.7 %	33.33 %	33.33 %
Shelf life	10	15	15	18	18	12	12

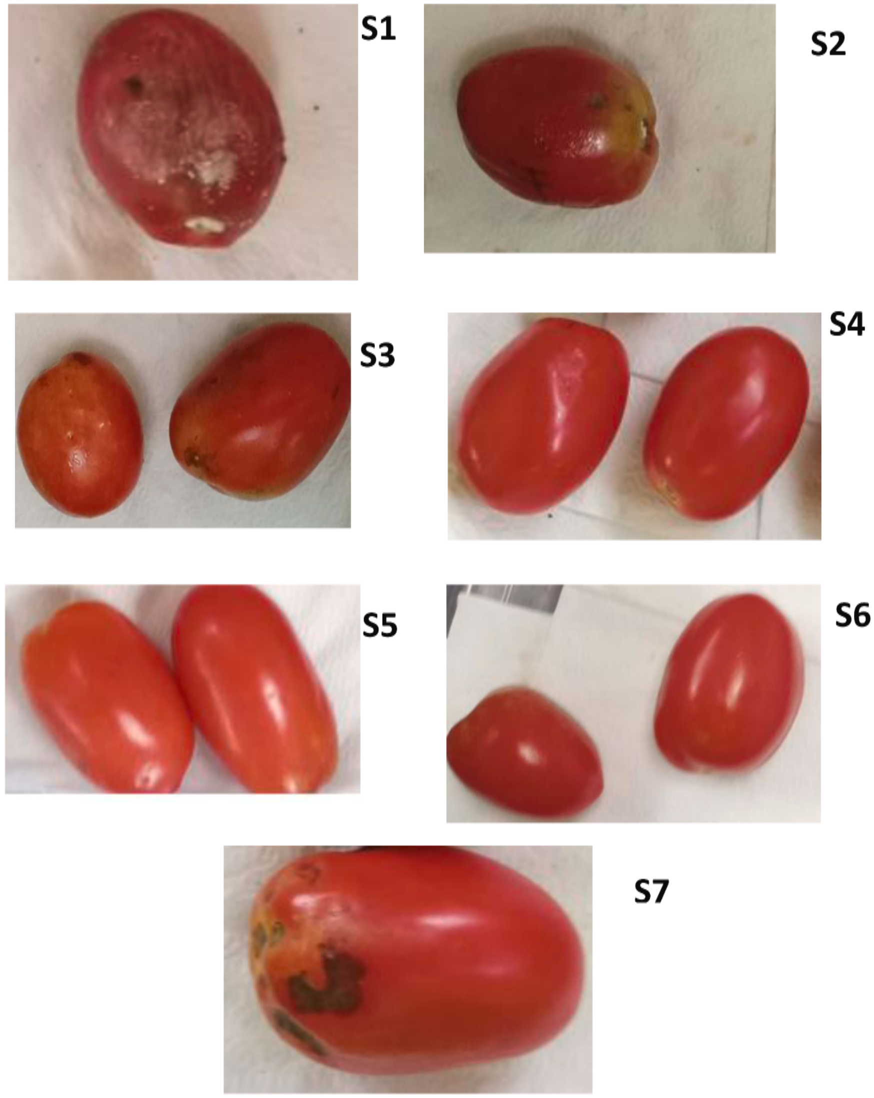

Fig. 5. The tomatoes appearance on 20th day of storage, where (S1= control, S2=1 % v/v macadamia nut oil +1 % w/v chitosan, S3=2 % v/v macadamia nut oil +1 % w/v chitosan and S4= 2.5 % v/v macadamia nut oil +1 % w/v chitosan, S5=1 % v/v macadamia nut oil, S6=2 % v/v macadamia nut oil and S7= 2.5 % v/v macadamia nut oil).

Sinha, 2022; Hesami et al., 2021).

4.1. Total phenolic and flavonoid content

Edible coatings can produce abiotic stress on fruits, modifying their metabolism and affecting the production of secondary metabolites such as phenolic and flavonoid compounds (Saidi et al., 2021). Application of edible coatings to tomato fruit has been associated with an accumulation of phenolic compounds, flavonoid and ascorbic acid, thereby enhancing the antioxidant capacity of the fruit (Dávila-Aviña et al., 2014). The accumulation of phenolic compounds may be facilitated by PAL activity, which is activated under stress conditions. Previous studies have demonstrated that low O_2 (2.5 KPa) and high CO_2 (7 kPa) concentrations can elevate the production of phenolic compounds in fresh-cut melons during storage, a phenomenon associated with oxidative stress (Oms-Oliu, Odriozola-Serrano, Soliva-Fortuny & Martín-Belloso, 2008). Similarly, grapes treated with edible chitosan coatings exhibited an increase in PAL enzyme activity, responsible for synthesizing phenolic compounds (Khalili et al., 2022). Total phenolic content (TPC) increased with the storage duration and ripening of tomatoes. However, in our study, the total phenolic content for coated tomatoes was found to be lower compared to control samples, as depicted in Fig. 1. These findings align with the antioxidant activity observed in various samples of tomatoes treated with macadamia nut oil. This could be attributed to the presence of phytochemicals like tocopherol, capable of donating hydrogen ions to free radicals, thereby slowing down the oxidation of phenolic compounds and flavonoid, thus preserving the quality of tomatoes. Moreover, the presence of fatty acids in macadamia nut oil may create a barrier on the active site of polyphenol oxidase, thus reducing enzymatic browning of tomato fruits (Bahmid et al., 2023). The lower values of phenolic and flavonoid content could be attributed to the presence of antioxidant compounds such as tocopherol in macadamia nut oil, capable of scavenging reactive oxygen species (ROS), thereby reducing or eliminating stress factors that trigger the synthesis of SOD, CAT, and APX enzymes (Bodoira & Maestri, 2020). A similar phenomenon was observed in a study where an *Aloe vera* gel coating combined with *Fagonia indica* plant extract maintained higher phenolic activity in sapodilla fruit, likely due to the presence of tocopherol and SOD, which can neutralize ROS (Khaliq, Ramzan & Baloch, 2019; Ozougwu, 2016). Additionally, higher phenolic content in plants has been linked to increased resistance to pathogens, as some flavonoid exhibit inhibitory activity against organisms responsible for plant diseases (Górniak, Bartoszewski & Króliczewski, 2019). Similar findings were reported in a study investigating the effects of coatings comprising Arabic gum, cinnamon oil, and sodium caseinate on guava (Murmu & Mishra, 2018).

4.2. Ascorbic acid content

Ascorbic acid content typically decreases with ripening and storage time, a phenomenon observed in various fruits including tomatoes (Steelheart et al., 2020). Being water-soluble, ascorbic acid is particularly susceptible to oxidation, especially with slight increases in temperature (Bradshaw, Barril, Clark, Prenzler & Scollary, 2011). However, in this study, the decline in ascorbic acid content was slower in tomatoes treated with coatings S5 and S4 throughout the storage period, as depicted in Fig. 4. This slower decrease suggests that the coatings may have inhibited the degradation of ascorbic acid during ripening, although not completely preventing its synthesis. Interestingly, while a general trend of increasing ascorbic acid content followed by a decline during full ripening was observed, this study demonstrated a slight decrease in ascorbic acid content for coated tomatoes compared to uncoated ones. The observation was possibly attributed to the presence of oleic acid in the coatings, which may interfere with the active site of ascorbate oxidase, thereby reducing the breakdown of ascorbic acid. This effect could be further enhanced by the formation of a protective layer over the tomato skin, limiting oxygen access (Mellidou, Keulemans, Kanellis & Davey, 2012). Moreover, the increase in ascorbic acid during ripening followed by a decrease afterward is consistent with previous studies on other fruits like sapota that suggesting a common pattern across different fruit types (Rodríguez-Zapata et al., 2015). These findings highlight the potential of coatings in preserving the ascorbic acid content of tomatoes during storage, contributing to their overall nutritional quality and extending their shelf life. Further research could delve into optimizing coating formulations to maximize this preservation effect and improve post-harvest handling practices for perishable produce.

4.3. Physiological weight loss

A reduction in weight loss was observed in coated tomatoes, specifically those treated with 1 % macadamia nut oil. This decrease could be attributed to the presence of a protective layer provided by oleic acid. This protective layer likely forms around the epidermal cell layer and cuticle of the tomato surface, reducing the transpiration process and thereby lowering vapor pressure. In addition, coating fruits minimizes transpiration by forming a layer on the fruit surface, either partially or completely covering stomata, lenticels, and micro-pores, thus creating a semi-permeable barrier to gas exchange and ultimately reducing transpiration (Kumar & Saini, 2021). This conclusion is supported by a study on Tomato "Chonto" (*Solanum lycopersicum L.*) using chitosan-E essential oil-based edible coatings under low-temperature storage (Peralta-Ruiz et al., 2020). Similarly, a comparable trend in weight loss was observed between non-coated (3.41 %) fruits and fruits coated with commercial carnauba-based (1.63 %) coatings after 15 days at 12.5 °C. This finding aligns with previous studies indicating that wax application significantly contributes to the reduction in weight loss of tomatoes (Abhirami, Modupalli & Natarajan, 2020). Edible materials such as whey protein isolate, xanthan gum, and clove oil used for coating tomatoes induce high relative humidity in the surrounding atmosphere of the tomato fruit, thereby reducing the moisture gradient to the exterior (Nor & Ding, 2020). Other scholars have also reported that tomatoes lose water at the stem scars (Fich, Fisher, Zamir & Rose, 2020). This current study further corroborates this observation, as depicted in Fig. 3, where uncoated tomatoes experienced significantly higher weight loss compared to treated tomatoes.

4.4. Color changes

Fruit quality deterioration is primarily attributed to enzymatic browning, facilitated by peroxidase and polyphenol oxidase enzymes (Singh et al., 2018). Accelerated lycopene production in the presence of oxygen, coupled with ethylene action, leads to color variation, a characteristic sign of ripening (Fich et al., 2020). The delayed formation of red color in coated tomatoes is associated with alterations in the fruit's internal atmosphere, resulting in elevated levels of CO_2 and reduced levels of O_2, which affect the maturation process. Polygalacturonase (PG) is an enzyme responsible for pectin disassembly during fruit ripening. Hence, the presence of oleic acid and other compounds in macadamia nut oil and chitosan formulations limits the activity of polygalacturonase, (Buthelezi, Magwaza & Tesfay, 2019) thereby slowing down metabolic reactions such as chlorophyll conversion to carotenoids, pectin disassembly, and ripening, which affect fruit color.

In a separate study, the color of chitosan-coated tomatoes was subjectively evaluated after 22 days of storage, revealing that control tomatoes ripened faster than their coated counterparts, as evidenced by the higher red color intensity observed in the chitosan-coated fruits (Safari, Ding, Juju Nakasha & Yusoff, 2020). Mature green tomato fruits, both waxed and non-waxed, stored at different temperatures (12 and 5 °C), exhibited variations in skin color and pigment content. Waxed fruits displayed a delay in color development and ripening (Duan et al., 2023). The use of wax and storage at low temperatures resulted in a delay in chlorophyll degradation and lycopene synthesis (Zacarias, Cronje & Palou, 2020). Therefore, waxing of tomato fruits facilitated the delay of the maturation process. Natural changes in chemical composition, acetaldehyde, and ethanol content were unaffected by the studied coatings. Lipid nanoparticle coatings were employed to extend the post-harvest life of tomatoes, as indicated by chroma results. The decrease in chlorophyll pigments and increase in carotenoid synthesis correlated with the fruit's color change from green to yellow or red (Poovai, Kumaran, Iyengar, Kalpana & Ramasubramaniyan, 2023). Additionally, the hue value gradually decreased for coated tomato fruits but rapidly for non-coated fruits, signifying the transition from green (mature green) to red (ripe) on the tomato fruit's outer surface as it ripened.

4.5. Decay percentages

Decay percentages and weight losses were used to determine directly the shelf life of tomatoes. The coated tomatoes exhibited lower levels of decay and better moisture retention compared to their uncoated counterparts. These parameters are closely linked to the ripening index, with higher ripeness associated with increased decay percentages and weight losses. Such trends were prominently observed in uncoated tomatoes, contrasting with the outcomes for coated tomatoes in this study. The delayed ripening observed in coated samples may be attributed to the formation of a semi-permeable film around the tomatoes, serving as a barrier against gas movement, particularly oxygen, carbon dioxide, and water vapor. This barrier likely modified the atmosphere surrounding the tomato samples, creating conditions conducive to sustaining their basic metabolic processes during storage in the postharvest shed. In contrast, the early ripening observed in non-coated samples can be attributed to the availability of oxygen, which facilitates cell tissue rupture, rendering tomatoes more susceptible to fungal spoilage(Maringgal, Hashim, Tawakkal & Mohamed, 2020) and resulting in higher decay rates. Similar effects of edible coatings on the quality of fresh blueberries under ambient conditions have been reported in previous studies (Duan, Wu, Strik & Zhao, 2011). Among the coated tomato samples, those treated with S4 and S5 demonstrated prolonged shelf life, as evidenced by a higher number of decay-free tomatoes noted after 18 days. Therefore, these formulations could be considered suitable for extending shelf life.

5. Conclusion

The effectiveness of macadamia nut oil combined with chitosan in preserving the post-harvest quality of tomatoes was successfully evaluated using a dipping method. Antioxidant properties such as total phenolic content, total flavonoid content, ascorbic acid, and physical characteristics like color, decay percentages and percentage weight losses of tomatoes were assessed over a 20-day storage period. The results revealed significant differences between uncoated tomatoes and those coated with 1 % macadamia nut oil. The uncoated tomatoes exhibited higher total phenolic content by 5.276 mg GAE/100 g and total flavonoid content by 48.38 mg/100 g. The lower weight loss and higher amounts of ascorbic acid was observed for tomatoes coated with macadamia oil compared to uncoated tomatoes. Additionally, the physical quality parameters such as color and decay percentages indicated the superior stability of tomatoes coated with 1 % macadamia nut oil compared to other treatment groups. Therefore, the application of macadamia nut oil edible coating proved to be successful in preserving the antioxidants and physical properties of tomato fruits. However, more investigations are required on anti-microbial effects of the applied coating to enhance understanding on its performance.

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Ethical statement

This work didn't use animals and/or human

CRediT authorship contribution statement

Tlehema Gwandu Umbayda: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Anthony Daniel Funga:** Writing – review & editing, Visualization, Supervision, Methodology, Formal analysis, Conceptualization. **Alinanuswe Joel Mwakalesi:** Writing – review & editing, Visualization, Supervision, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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