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Article

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Posted Date: November 25th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11685301/v1

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Additional Declarations: No competing interests reported.

Optimizing edible coating dipping duration to preserve quality of 'Classic Round' tomato (*Solanum lycopersicum* L.) during storage

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Abstract

Tomato (*Solanum lycopersicum* L.) is considered as a global significant crop owing to its high nutritional profile; however, its climacteric nature leads to rapid quality deterioration. This study evaluated the effects of Citrashine™ edible coating dipping duration (0, 2, 4, and 6 min) and cold storage durations (7, 14, 21, and 28 days at 10 °C) on the maintenance of physicochemical properties and bioactive compounds. A significant interaction ($P < 0.05$) was observed between dipping and storage duration across all parameters. A 4 min dipping duration was the most effective treatment for maintaining physical integrity, minimizing physiological weight loss, preserving the highest firmness and delaying colour development, ripening and senescence. Conversely, a 2 min dipping duration was optimal for retaining bioactive constituents, yielding the highest retention of total phenolic content (TPC), total flavonoids content (TFC), vitamin C, lycopene, and proline. These findings demonstrated that Citrashine™ dipping duration of 2 min and 4 min serve as effective postharvest treatments to preserve the commercial quality and nutritional value of 'Classic Round' tomatoes during extended cold storage.

Keywords: Bioactive compounds, Fruit firmness, Postharvest quality, Shelf life, *Solanum lycopersicum*

Introduction

Tomato (*Solanum lycopersicum* L.) is a dominant vegetable crop, ranking second only to potato in production and leading the processed vegetable market, with global annual yield reaching 186.1 million tons [1,2]. Despite this high production capacity, nearly 1.3 billion tonnes of all food produced for human consumption is wasted annually across the supply chain [3,4]. Tomatoes are vulnerable and suffering postharvest losses ranging from 25% to 42% globally due to improper handling, inadequate infrastructure and their highly perishable nature [2,5]. These losses represent a significant barrier to achieving the United Nations Sustainable Development Goal (SDGs) specifically SDG 2 (Zero hunger) and SDG 12 (Responsible consumption and production) [4,6]. Furthermore, the environmental impact of such waste is staggering, contributing to about 3.3 gigatons of CO_2 emission and accounting for 8% of the world's total greenhouse gas emission [4].

Beyond the loss, tomato is a vital source of bioactive compounds, including lycopene, carotenoids, phenolics, and flavonoids, which are essential for mitigating oxidative stress in human beings [7,8]. In South Africa, tomatoes represent 24% of total vegetable output, yet the industry faces significant challenges due to production fluctuations and high perishability [9]. As a climacteric fruit, tomato undergoes rapid postharvest respiration, transpiration and ethylene production, which lead to accelerated softening and nutrient degradation [1,7]. Nutritional degradation is a critical concern, as tomatoes can lose up to 70% of their vitamin C content in just one week of non-optimal storage [10]

Traditional postharvest technologies such as refrigeration and synthetic fungicides are often limited by high costs and concerns regarding toxic residues in food chain [11,12]. Consequently, there is a growing consumer demand for sustainable, residue free preservation technologies such as edible coatings [13,14]. These coatings, derived from natural biodegradable polymers, form a semi-permeable physical barrier that regulate gas exchange (O_2 and CO_2) and limit moisture loss [15,16]. By creating a modified internal atmosphere (MIA), these coating slow down respiration rates and ripening related biochemical reactions, thereby extending shelf life while maintaining the fruit's aesthetic appeal and nutritional profile [15]. Citrashine™ , a commercial wax widely used for citrus preservation, has shown potential for weight loss reduction and quality maintenance in various fruit, making it a viable candidate for tomato preservation [17].

The efficacy of an edible coating is strictly dictated by application parameters, particularly dipping time, which influences layer thickness, uniformity and surface adhesion [18]. While

insufficient dipping time provides an inadequate barrier against water loss and pathogen attack, excessive dipping can excessively restrict gas exchange, inducing O_2 starvation, anaerobic fermentation and the development of undesirable off-flavour [19,20]. Although Citrashine™ is known to improve aesthetic appeal, the interaction between dipping time and storage duration on simultaneous retention of physicochemical properties and bioactive compounds in 'Classic Round' tomatoes remains poorly understood. In view of the above, the objective of the current study was to investigate the interactive effect of dipping time and storage duration on the quality attributes and bioactive profile of 'Classic Round' tomatoes during extended cold storage.

Materials and Methods

Study area and materials

Fresh 'Classic Round' tomatoes (*Solanum lycopersicum* L.) of uniform size, color (at the breaker) and free from visual bruises or mechanical injuries were obtained from commercial fresh market. Fruit were immediately transported to the Plant Production laboratory at the University of Limpopo, South Africa (23°53′09.9″S; 29°44′17.7″E) for treatment evaluation. Upon arrival, fruit were sorted and sanitized for 3 minutes using a disinfectant solution Sporekill® at 2.5% and then air dried for 1 h at ambient temperature (24 ± 2 °C).

Coating treatments and experimental design

The experiment was laid out as 4 × 4 factorial experiment arranged in a completely randomized design (CRD) with three independent replicates (with 5 fruit per replicate per sampling interval, totaling 20 fruit). The two experimental factors comprised: (1) Citrashine™ edible coating immersion duration at four levels: 0 (untreated control), 2, 4 and 6 min [(Citrashine (Pty) Ltd., Johannesburg, South Africa)]. (2) Cold storage duration at four intervals: 7, 14, 21 and 28 days. Fruit were submerged in undiluted Citrashine™ coating solution according to their assigned duration, while control fruit were left uncoated. After dipping, fruit were drained and allowed to dry at ambient temperature (24 ± 2 °C) for 2 h to ensure complete film adhesion and surface drying. Coated and uncoated fruit were subsequently stored in a cold room at 10 ± 1 °C and 90% relative humidity for up to 28 days, with batches sampled destructively and non-destructively at 7 days intervals.

Physiological weight loss

Fruit weight loss was determined gravimetrically at 7 day sampling intervals (day 0, 7, 14, 21 and 28) using a precision digital weighing balance (accuracy ±0.01 g: HBC1002 Max, Adam Equipment, Milton Keynes, UK) following the method described by [21]. The percentage physiological weight loss was calculated according to Eq. (1)

$$\text{Physiological weight loss (\%)} = \left(\frac{Wo-Wt}{Wo}\right) \times 100 \qquad (1)$$

Where Wo is the initial fruit mass on day 0 (g) and Wt is the mass of the same fruit on the designated sampling day (g).

Fruit firmness

Fruit firmness was evaluated using a hand-held pocked fruit penetrometer (Model FT 327, TR Turoni, Forli Italy) fitted with a stainless steel plunger tip. The tip was pressed into the fruit until penetration occurred and the force displayed on the dial gauge was recorded in Newtons (N).

Fruit surface color

The surface color of 'Classic Round' tomato were determined using a Minolta Chromameter CR-400 (Model CR-400, Minolta Corp, Osaka, Japan) calibrated prior with a standard white calibrated plate [22]. Color measurements were recorded at three equidistant points along the equatorial plane of each fruit using CIE L*, a*, b* color space: L* value represent lightness or brightness, a* represent redness (+) or greenness (-) and b* represent yellowness (+) or blueness (-).

Total soluble solids (TSS)

The total soluble solids (TSS) content tomato juice was determined using a portable hand digital refractometer (Model RHB 32ATC, Fujian, China). A drop of juice (sample) was placed onto the clean optical prism, and reading were directly recorded in ^{o}Brix. Between consecutive measurements, the prism was rinsed thoroughly with distilled water and dried with tissue paper.

Titratable acidity (TA)

Total titratable acidity was determined using the titrimetric evaluation in accordance with AOAC standard procedures (Horwitz 1960). A 5 ml of tomato juice was diluted with 10 mL of distilled water, followed by addition of 2-3 drops of 1% (w/w) phenolphthalein indicator solution. The diluted sample was titrated against standardized 0.1 N NaOH (sodium hydroxide)

using a precision glass burette until the solution changed to faint pink color indicating an endpoint. Titratable acidity was calculated as the percentage citric acid equivalent on a fresh weight basis according to Eq. (2)

$$\text{Titratable Acidity (\% citric acid)} = \left(\frac{V(NaOH) \times N \times 0.064}{Vsample}\right) \times 100 \qquad (2)$$

Where $V_{(NaOH)}$ is the volume of NaOH consumed (mL), N is the normality of the NaOH titrant (0.1 N), 0.064 is the milliequivalent factor for citric acid (g meq $^{-1}$), and V_{sample} is the initial volume of tomato juice (5 mL)

Maturity index (TSS:TA ratio)

The maturity index (sugar to acid ratio) was calculated as the ratio of TSS to TA according to Eq. (3)

$$\text{Maturity index (MI)} = \frac{\text{TSS (obrix)}}{\text{TA (\%)}} \qquad (3)$$

Total phenolic content (TPC)

The TPC was determined using the Folin-Ciocalteu reagent method [23]. A methanol extract (0.5 mL) was mixed with 2.5 mL of 10% (v/v) Folin-Ciocalteu reagent and allowed to react for 5 min, followed by the addition of 2.0 mL of 7.5% (w/v) sodium carbonate (Na_2CO_3) solution. The reaction mixture was incubated in the dark at room temperature (25 ± 2 °C) for 60 min. Absorbance at 750 nm was determined using a microplate reader (Thermo Fisher Scientific multiskan FC 357, Shanghai, China) against a reagent blank. A calibration curve was prepared using a tannic acid concentrations ranging from 1.25 to 0.08 mg/mL and TPC was expressed as milligrams of tannic acid standard per gram of fresh weight (mg TAE g $^{-1}$ FW)

Total flavonoids content (TFC)

The TFC was quantified using the aluminum chloride colorimetric assay [23]. Briefly, 1.0 mL of tomato extract was transferred into a 10 mL volumetric flask containing 4.0 mL deionized water, followed by the addition of 0.3 mL of 5% (w/v) sodium nitrite ($NaNO_2$). After 5 min of incubation, 0.3 mL of 10% (w/v) aluminum chloride ($AlCl_3$) was added. After an additional 6 min, 2.0 mL of 1 M sodium hydroxide (NaOH) was added and the solution was diluted to a final volume of 10 mL with deionized water. The absorbance of pink mixture was measured at 510 nm using a spectrophotometer (Model UV-1800, Shimadzu, Ltd., Japan). TFC was

calculated against a quercetin calibration curve and expressed as milligrams of quercetin equivalent per gram of fresh weight (mg QE) g^{-1} FW).

Vitamin C

Vitamin C content was determined titrimetrically using the 2,6-dichlorophenolindophenol (DCPIP) dye method [24]. Fresh tomato juice (10 mL) was combined with 0.4% (w/v) oxalic acid solution and adjusted to a final volume of 100 mL. A 5 mL of extract was titrated against standardized DCPIP solution until a persistent faint pink endpoint was observed for at least 15 s. Vitamin C concentration was calculated based on the dye factor and expressed as milligrams per 100 g of fresh weight (mg 100 g^{-1} FW).

Lycopene content

Lycopene content was determined spectrophotometrically following the extraction method described by [25]. Tomato juice (1.0 g) was homogenized in 20 mL of a solvent mixture consisting of hexane, acetone and ethanol (2:1:1, v/v/v). After phase separation, the upper hexane layer containing lycopene was collected and absorbance was measured at 530 nm using a UV-Vis spectrophotometer (Model UV-1800, Shimadzu Corp., Kyoto, Japan) against a solvent blank. Lycopene concentration was calculated using its specific extinction coefficient (17.2×10^4 M^{-1} cm^{-1}) and expressed as micrograms per gram of fresh weight (μg g^{-1} FW).

Proline

Proline concentration was evaluated using the acid ninhydrin method [26]. Tomato tissue (0.5 g) was homogenized in 5 mL of 3% (w/v) aqueous sulfosalicylic acid and centrifuged at 10 000 × g for 10 min. A 2.0 mL aliquot of the supernatant was combined with 2.0 mL of glacial acetic acid and 20 mL of freshly prepared acid ninhydrin reagent (1.25 g ninhydrin dissolved in 30 mL glacial acetic acid and 20 mL of 6 M phosphoric acid). The mixture was heated in a boiling water bath at 100 °C for 60 min and cooled rapidly in an ice bath. The reaction mixture was extracted with 4.0 mL of toluene and vortexed vigorously for 30 s. The absorbance of the upper toluene phase was measured at 520 nm against a toluene blank. Proline concentration was determined from a standard curve of L-proline and expressed as micrograms per gram of fresh weight (μg g^{-1} FW).

Statistical Analysis

All experimental data were subjected to two-way analysis of variance (ANOVA) using GenStat statistical software (21st Edition, VSN International, Hemel Hempstead, UK) to evaluate the main effect of coating dipping duration, storage period and their interaction. Prior to ANOVA, percentage data were arcsine square-root transformed where appropriate and the underlying assumptions of normality and homogeneity of variance were verified the Shapiro-Wilk and Levene's tests, respectively. Significant differences between treatment means were separated using Tukey's honestly significant difference (HSD) test at a significant level of $p \leq 0.05$.

Results and discussion

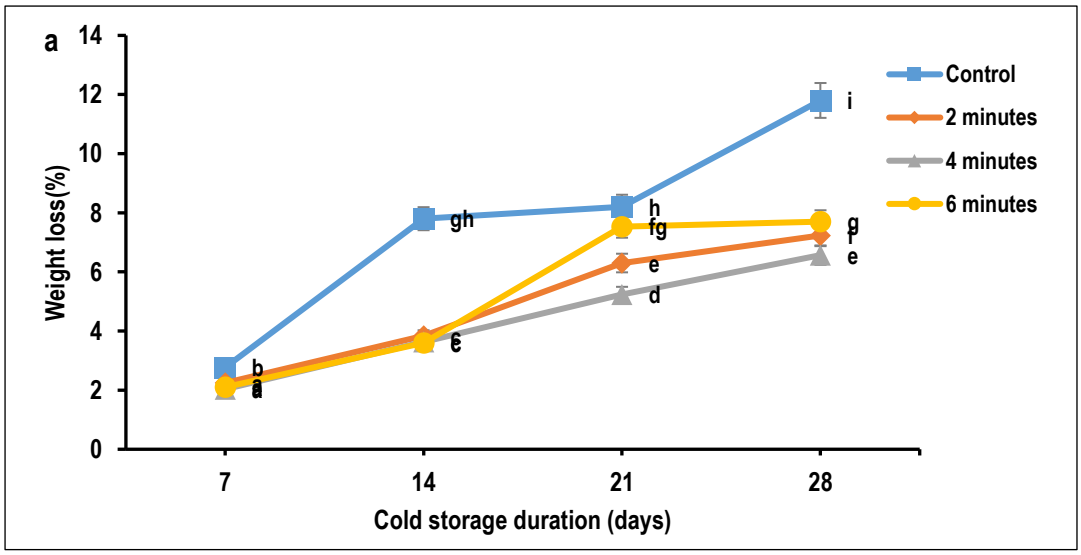
Weight loss, firmness and color

The application of Citrashine™ edible coating significantly influenced the physical integrity of 'Classic Round' tomatoes during 28 days of cold storage at 10 °C. As displayed in Fig. 1, a 4 min dipping duration was the most effective treatment for maintaining the physical quality attributes. This treatment consistently minimized physiological weight loss to 6.5%, representing a significant reduction compared to the 11.8 % loss observed in the untreated fruit. Furthermore, fruit dipped for 4 min maintained the highest firmness of 24.36 N at 28 days, whereas the firmness of untreated fruit declined to 13.41 N by the end of the storage (Fig.1b). This improved in retention of physical integrity resulted from the formation of semi-permeable physical barrier on the fruit surface, which effectively blocks epidermal openings such as trichome-associated transcuticular polar pores [27]. Consequently, this protective layer reduced both transpiration and respiration rates, which are the main biological drivers of postharvest weight loss in climacteric produce [28]. A 4 min dipping duration provided an optimal coating thickness and uniformity, thereby ensuring continuous barrier protection over the extended cold storage. These findings corroborate the results of [29], who observed that a 3 min garlic and capsicum based dipping was effective for reducing weight loss in 'Fetane' and 'Melkashola' tomatoes.

The delay of fruit softening in 4 min treated fruit is largely attributed to the coating's ability to slow down enzymatic cell wall degradation. Softening in tomatoes is encouraged by breakdown of structural polysaccharides such as hemicellulose and the dissolution of pectin by enzymes such as polygalacturonase (PG) and pectin methyl esterase (PME) [30]. By creating a modified internal atmosphere (MIA) and slowing down ripening-related metabolic processes, the Citrashine™ edible coating effectively delayed tissue softening [7]. This delay in softening is

consistent with findings by [31], who reported that edible coating effectively suppress cell wall softening enzyme activity, such as PG and cellulase, by reducing O_2 availability and metabolic rate. [32] observed similar outcomes, where a 4 min dipping time in carboxymethyl cellulase coating maintained higher firmness in citrus fruit than shorter dipping treatments. [33], also found that composite coating inhibited the expression of cell wall degradation enzymes in 'Sunrise' papaya.

The application of Citrashine™ influenced the color characteristics of 'Classic Round' tomato (Table 1). In our study, 4 min treated fruit maintained the highest L* values throughout the 28 cold storage period, reaching 37.67 compared to the decline of 24.59 in the untreated fruit. This retention of lightness/brightness suggests that the coating effectively minimized transpiration and surface dehydration, which are the primary drivers of fruit shriveling and surface dullness [15,34]. The significant lower L* values in the untreated are indicative of accelerated senescence and the possible development of surface spots due to moisture loss [35]. Interestingly, the 6 min dipping duration showed a lower L* value than 4 min dipping duration at day 28, likely due to anaerobic stress induced tissues darkening caused by overly restrictive gas barrier [19,20]. Redness (a*) values increased in all dipping durations as the fruit ripened, but the rate of increase was significantly moderated by the Citrashine™ coating (Table 1). The 4 min dipping duration resulted in the lowest a* values at day 28 compared in untreated. This delay in red color development is direct result of the MIA created by coating, which limits the O_2 availability required for lycopene biosynthesis and the degradation of chlorophyll [7,36]. These findings aligned with reports that edible coating can postpone the transition to red stage by slowing down respiratory and metabolic activities [37,38]. Consistent with the L* and a* changes, yellowness (b*) was better preserved in the 4 min treated fruit than in the untreated by the end of storage. Higher b* values in coated fruit suggest a reduced rate of oxidative degradation of yellow pigment carotenoids [39].



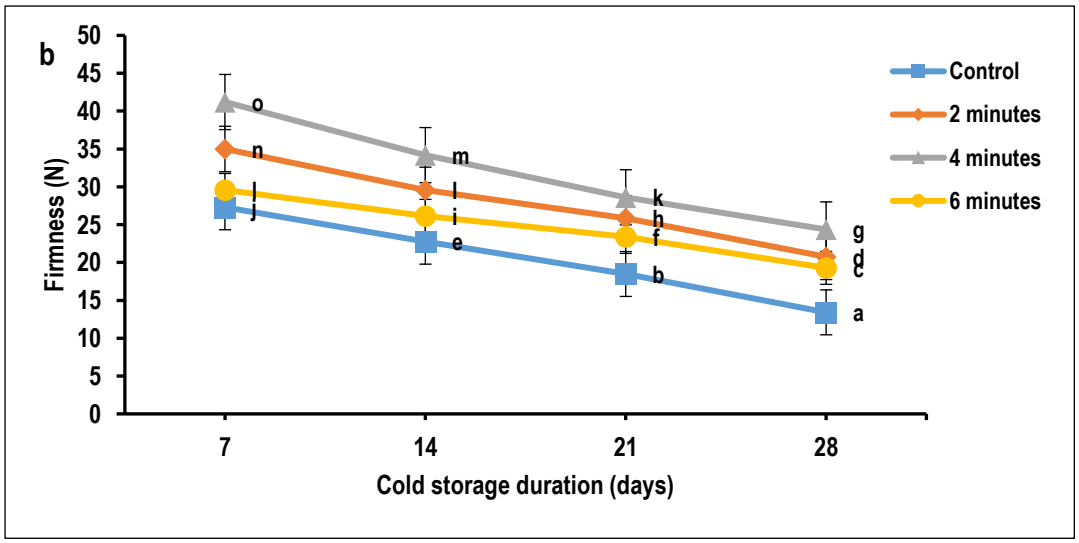


Fig. 1. Physiological weight loss percentage (**a**) and firmness loss (**b**) of 'Classic Round' tomatoes coated with Citrashine^{TM} at different dipping durations (0, 2, 4 and 6 min) during cold storage of 28 days at 10 °C.

Table 1. Effect of Citrashine™ dipping duration and cold storage duration on the surface colour parameters (L^*, a^*, and b^*) of 'Classic Round' tomatoes stored at 10 °C for 28 days.

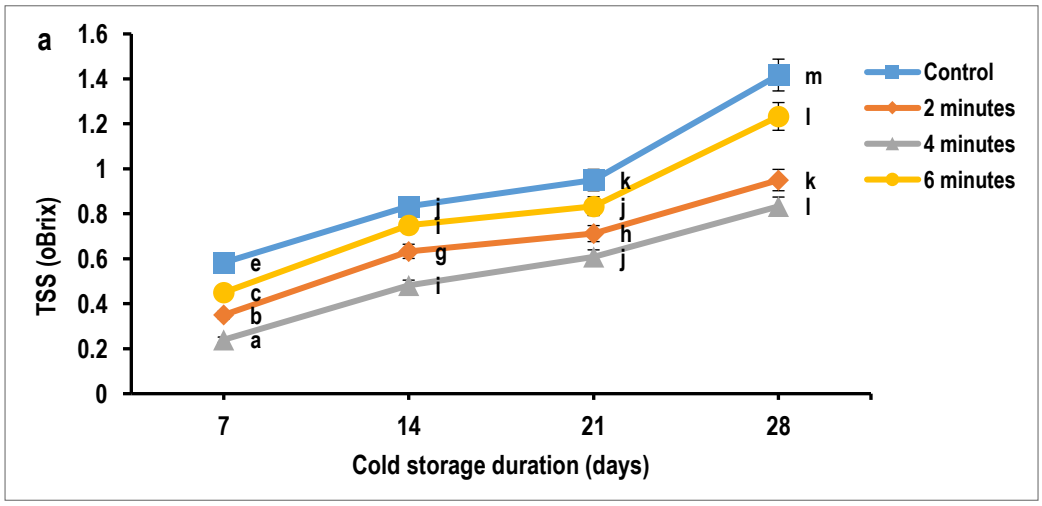
Color parameters		Cold storage days			
	Dipping duration (min)	**7**	**14**	**21**	**28**
a* (redness)					
	0	0.34^{e}	0.44^{i}	0.45^{i}	0.56^{k}
	2	0.23^{b}	0.30^{d}	0.35^{ef}	0.41^{h}
	4	0.20^{a}	0.27^{c}	0.30^{d}	0.38^{g}
	6	0.30^{d}	0.36^{fg}	0.40^{h}	0.49^{j}
b* (yellowness)	**0**	17.33^{i}	14.36^{g}	10.4^{c}	7.12^{a}
	2	18.73^{l}	17.26^{i}	14.36^{g}	10.98^{d}
	4	19.24^{m}	17.61^{j}	15.77^{h}	11.57^{e}
	6	18.04^{k}	15.77^{h}	12.7^{f}	8.68^{b}
L* (lightness)	**0**	39.98^{ef}	36.13^{cd}	31.56^{b}	24.59^{a}
	2	45.22^{h}	40.83^{efg}	36.16^{cd}	32.07^{b}
	4	49.48^{i}	43.27^{gh}	41.01^{fg}	37.67^{de}
	6	41.55^{fg}	39.98^{efg}	33.44^{bc}	26.94^{a}

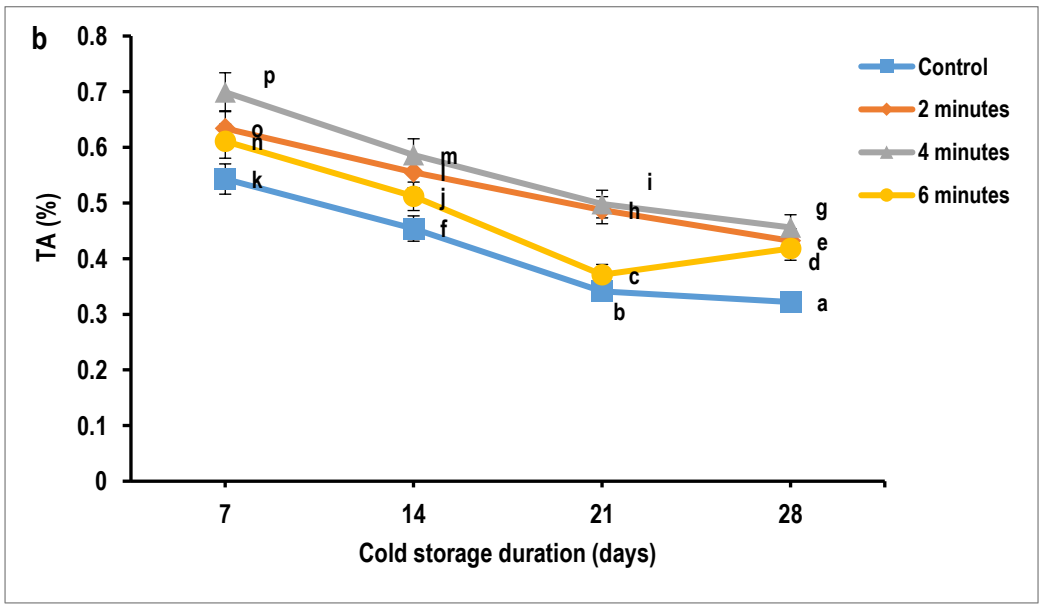
Values represent the means. Means followed by different superscript letters within the same color parameter are significantly different according to Tukey's HSD test at $P \leq 0.05$

Maturity and flavor dynamic (TSS, TA and TSS:TA ratio)

Total soluble solids (TSS) and titratable acidity (TA) serve as primary indicators of fruit ripening and key determinants of organoleptic flavor balancer [7]. Throughout cold storage, TSS increased due to enzymatic hydrolysis of structural polysaccharides and starch into simple sugars, a process exacerbated by moisture loss [31]. Concurrently, TA declines as organic acids including citric and malic acid are used as respiratory substrates to drive fruit's metabolic activities [7,40]. The current study found that a 4 min dipping duration significantly minimized these changes, maintaining the lowest TSS and highest TA level by day 28 (Fig. 2a, b). This stabilization suggests that the 4 min dipping duration reached an optimal thickness to retard metabolic rates without inducing anaerobic stress [31]. The retention of organic acids such as citric and malic is consistent with findings by [41], who observed that intermediate Citrashine™

dipping times best preserved acidity in orange. Similarly, bio-based coating have been shown to maintain higher TA by reducing the rate of transpiration and metabolic consumption of acids in other climacteric fruit such as mango and tomato [7,42]. Consequently, the TSS:TA ratio, which reflects the maturity, sweetness and flavor quality, increased most gradually in the 4 min treated fruit (Fig. 2c). By slowing down the rapid increase of this ratio, Citrashine™ effectively delayed the onset of over-ripeness and senescence, supporting the results reported by [43] in Aloe vera-coated cherry tomato. Furthermore, the ability of the coating to minimize moisture loss plays a dual role in stabilizing the sugar content over time, leading to more desirable flavor profile and extended postharvest shelf life [20].





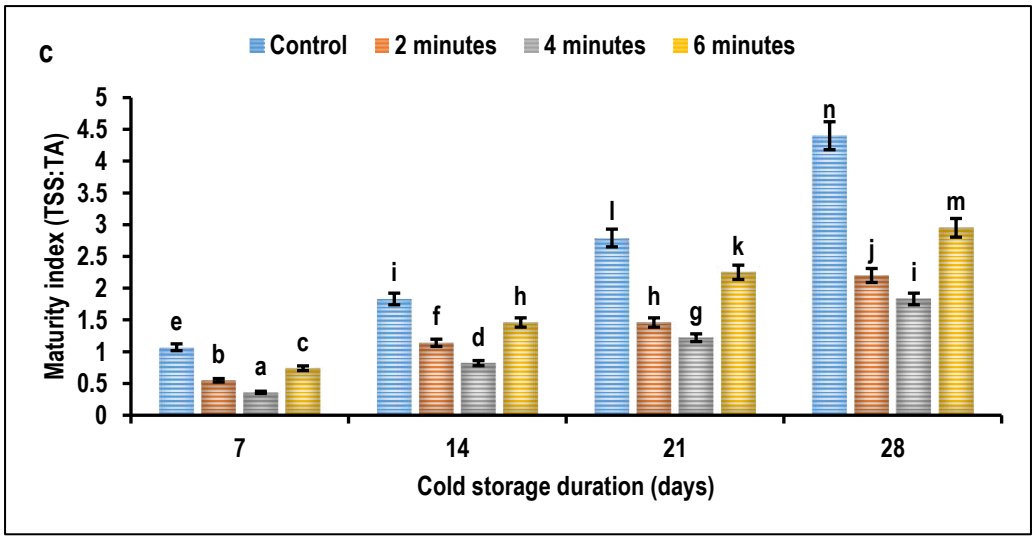


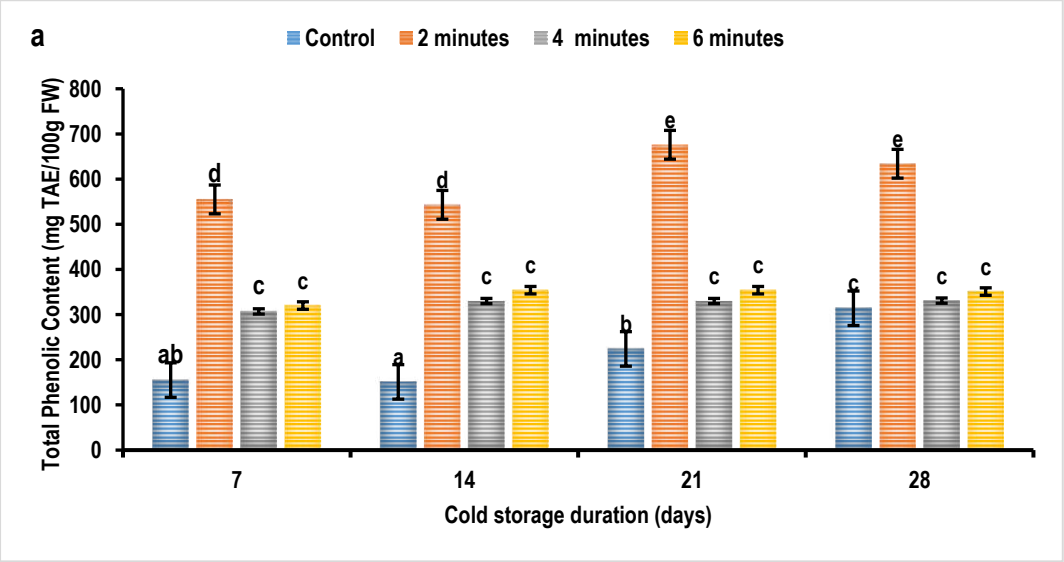
Fig. 2. Total soluble solids (**a**), titratable acidity (**b**) and TSS:TA ratio (**c**) of 'Classic Round' tomato coated with Citrashine^{TM} at different dipping durations (0, 2, 4 and 6 min) during cold storage of 28 days at 10 °C.

Bioactive compounds preservation and antioxidant capacity

While the 4 min dipping duration was optimal for maintaining physical integrity, the 2 min dipping duration Citrashine^{TM} dipping duration emerged as the ideal protocol for preserving bioactive compounds and antioxidant capacity including total phenolic content (TPC), total flavonoid content (TFC), vitamin C, lycopene and proline (Fig. 3 and 4). This variation suggests a clear metabolic compromise in postharvest management. While thicker coating provides a greater moisture barrier, they can also induce metabolic stress that impairs the synthesis and retention of bioactive compound. In general, TPC decreases during fruit ripening/storage as the results of enzyme oxidation driven by polyphenol oxidase (PPO) and peroxidase (POD) activity [20,42]. However, 2 min dipping duration maintained the highest TPC, reaching a peak at 21 days in the current study (Fig. 3a). This peak suggest that the 2 min dipping duration provided an optimal MIA, which was thin enough to minimize PPO and POD activities without triggering the cellular damage and anaerobic stress [20]. Studies on fresh cut apples showed that coating made from combining chitosan with vitamin C or blended whey protein/pectin effectively preserved phenolic content during storage [44,45]. Similarly, TFC remained more stable under the 2 min dipping duration, likely due to a moderate reduction in respiration that shielded flavonoids from oxidative degradation, a mechanism reported by [46] regarding the upregulation of antioxidant defense genes by biopolymer coating. Vitamin C, which declines during storage due to the activity of ascorbate oxidase, effectively maintained by 2 min dipping duration (Fig. 3a). The coating ability to act as a semi-permeable physical

barrier reduced O_2 permeability, thereby slowing the oxidative breakdown of ascorbic acid [20,42]. This protective mechanism aligns with the findings by [7], who observed that edible coating effectively restrict gas diffusion to retain high level of vitamin C in tomato.

Furthermore, lycopene which is the primary carotenoids and antioxidant in tomato was higher in fruit dipped for 2 min (Fig. 4b). The accumulation of lycopene is an aerobic process that occur as chlorophyll degrade during climacteric phase; 2 min dipping duration achieved an ideal balance. It was sufficient to provide a moisture barrier while remaining permeable enough to allow gas exchange necessary for pigment synthesis [7]. In contrast, longer dipping times (4 and 6 min) likely restricted O_2 severely, shifting the tomato fruit towards anaerobic fermentation and inhibiting the accumulation of lycopene [19]. In this study, proline, which serves as a vital stress protective amino acid, was higher in 2 min treated fruit (Fig. 4c). This high proline content indicates a sustained antioxidant defense mechanism that enhances the fruit ability to resist physiological deterioration and oxidation stress. This aligned with findings by [47] who showed that the application of chitosan-arginine NPs at 0.5% significantly increased proline content in plums during the storage period, reaching the highest concentration at the end of storage compared to control plums.



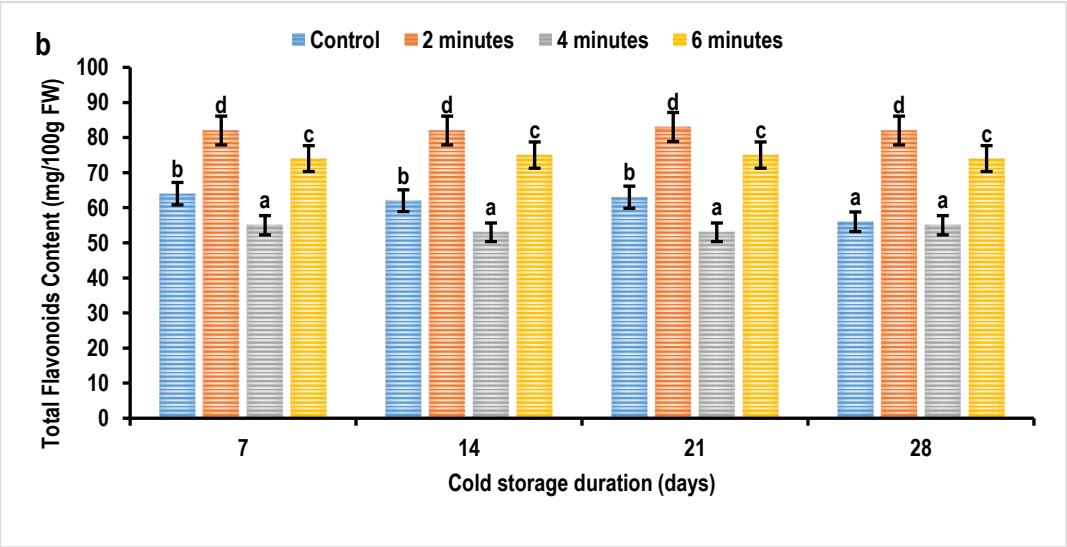
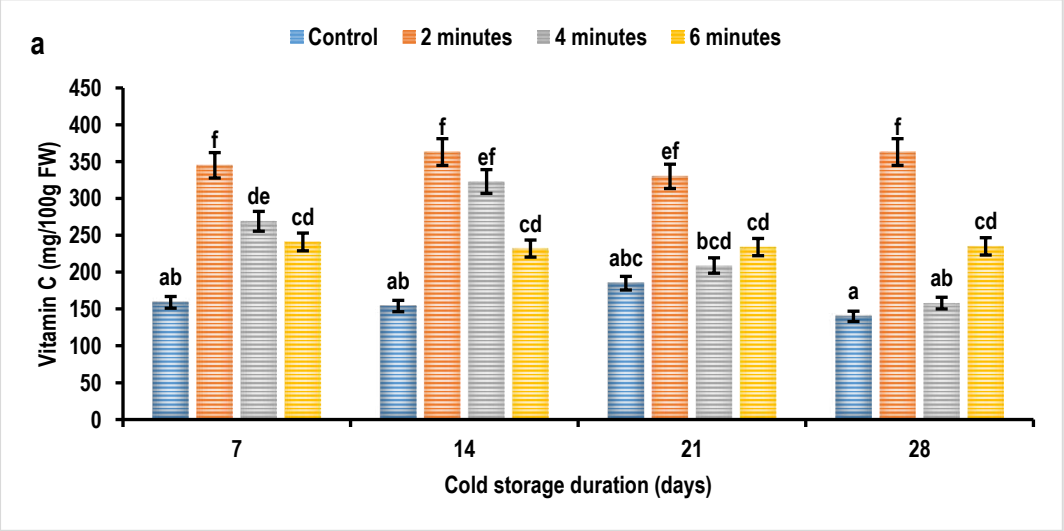


Fig. 3. Total phenolic content (**a**) and total flavonoid content (**b**) of 'Classic Round' tomato coated with Citrashine^{TM} at different dipping durations (0, 2, 4 and 6 min) during cold storage of 28 days at 10 °C.



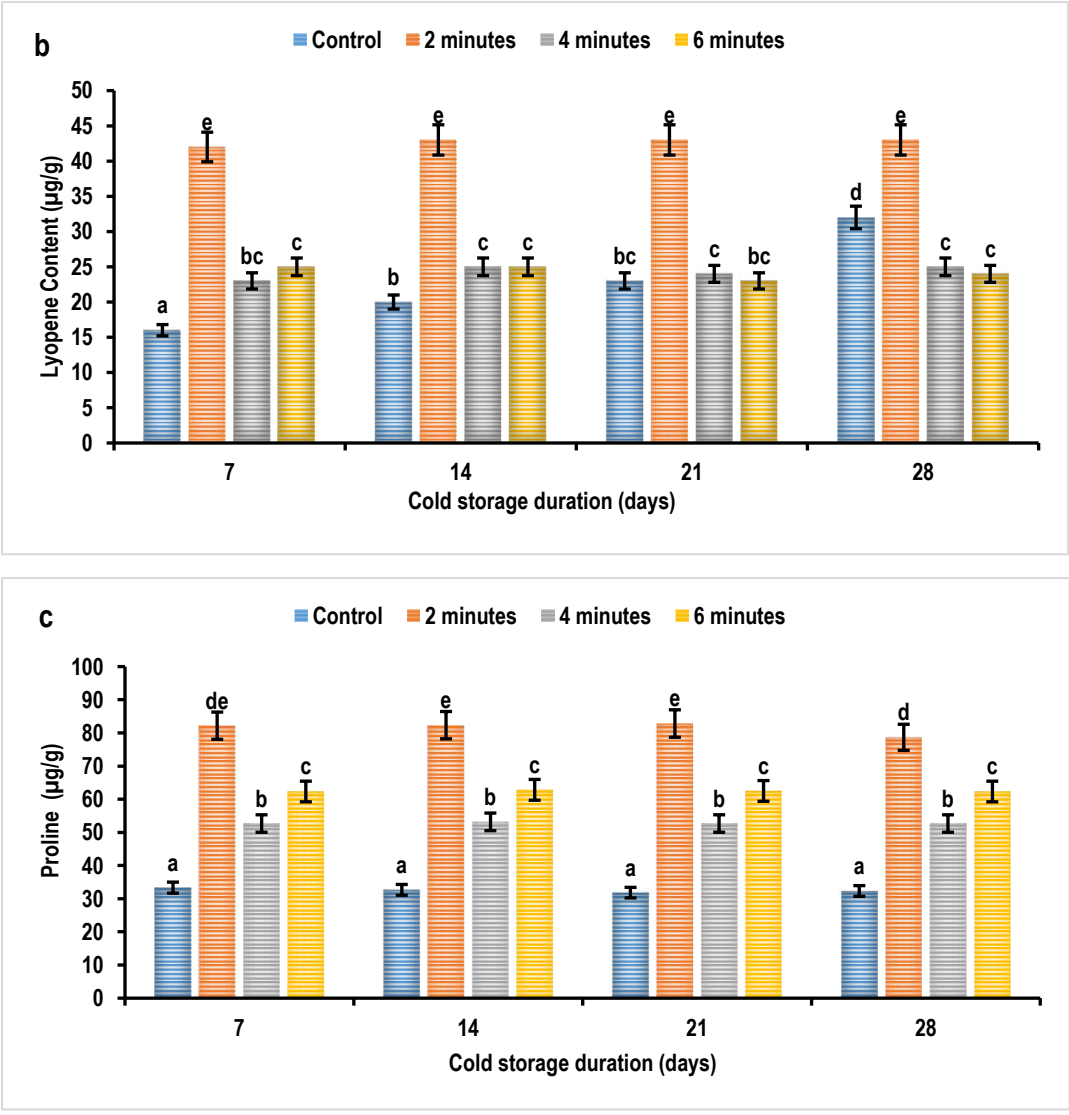


Fig. 4. Vitamin C (**a**), lycopene (**b**) and proline (**c**) of 'Classic Round' tomato coated with Citrashine^{TM} at different dipping durations (0, 2, 4 and 6 min) during cold storage of 28 days at 10 °C.

Conclusion

This study demonstrated that Citrashine^{TM} edible coating is an effective, sustainable postharvest technology for maintaining the quality and extending the cold storage life (28 days age at 10 °C) of 'Classic Round' tomatoes. The functional efficacy of the coating is largely influenced by dipping duration, which determines the physiological balance between creating a moisture barrier and maintaining normal fruit metabolism. A 4 min dipping duration was optimal treatment for preserving the physical integrity as it maintained physiological weight loss (6.50%), retarded tissue softening (24.36 N), and delayed color development and ripening. Conversely, a 2 min dipping duration was effective for preserving bioactive constituents,

yielding the highest retention of TPC, TFC, vitamin C, lycopene, and proline. Therefore, dipping durations of 2 min and 4 min represent effective postharvest treatments for maintaining the postharvest quality of 'Classic Round' tomatoes during extended cold storage. Future research should evaluate the incorporation of natural antimicrobial agents into Citrashine™ treatment to further enhance resistance against pathogen-induced decay.

Acknowledgments The authors express their gratitude to the Department of Plant Production, Soil Science and Agricultural Engineering (PPSAE), University of Limpopo for providing the research facilities and technical support necessary to conduct the study.

Authors Contributions All authors contributed to the study conception and design. Conceptualization and methodology: MSL, KS and NM; Formal analysis and investigation: MSL and MJM; Data curation: MSL; writing – original draft preparation: MSL; Writing and editing, Supervision and project administration: KS, MJM and NM. All authors read and approved the final manuscript.

Data Availability The datasets generated and analyzed during the current study are available from corresponding author upon reasonable request.

Competing Interests The authors have no relevant financial or non-financial interests to disclose

Consent to Publish Not applicable

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