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Effects of Gum Arabic-Calcium Chloride Composite Coating on Postharvest Quality and Antioxidant Properties of Cold-Stored Tarap (*Artocarpus odoratissimus*)

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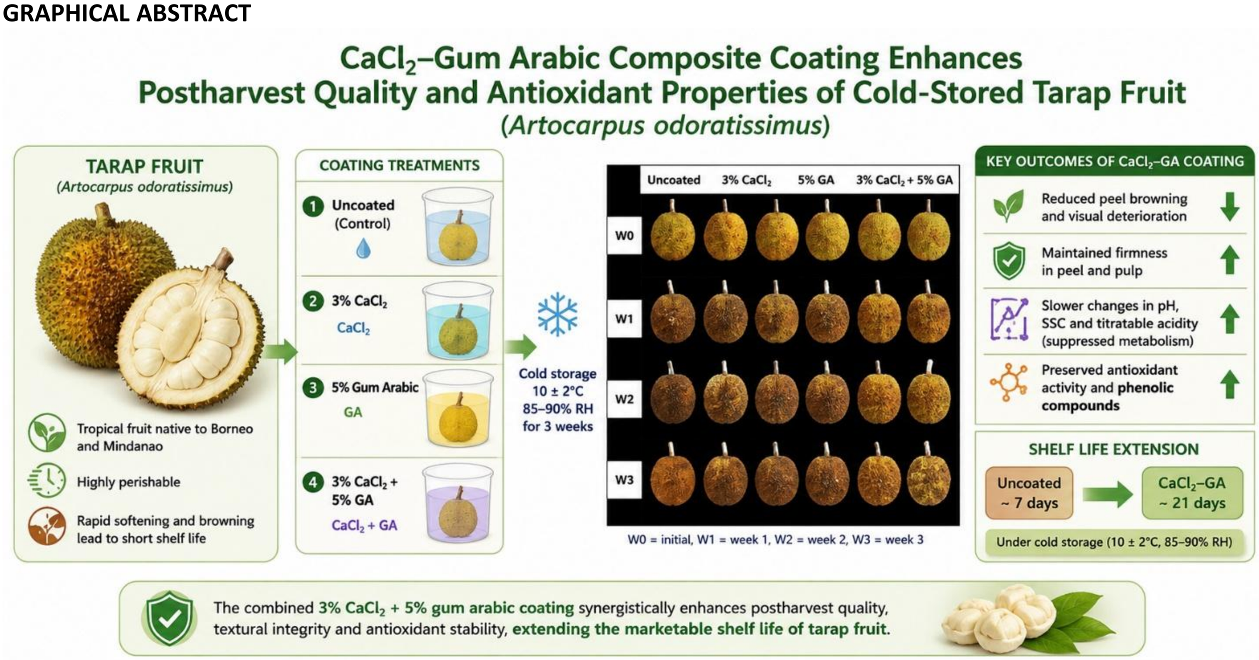
GRAPHICAL ABSTRACT



ABSTRACT

Artocarpus odoratissimus (tarap) is a tropical fruit native to Borneo and Mindanao and valued for its nutritional and economic benefits. However, its highly perishable nature and the absence of effective storage methods present significant challenges to maintaining quality and extending shelf-life. This study evaluated the effects of calcium chloride ($CaCl_2$), gum arabic (GA) and their combined application on the postharvest quality and antioxidant properties of tarap fruit during cold storage at 10±2°C and 85-90% relative humidity over three weeks. Four coating treatments were applied: (1) control (distilled water), (2) 3% $CaCl_2$, (3) 5% GA, and (4) a combined treatment of 3% $CaCl_2$ + 5% GA ($CaCl_2$-GA). The influence of these treatments on peel and pulp colour, firmness, pH, titratable acidity, soluble solids concentration, ascorbic acid content, total phenolic content and antioxidant activity was assessed throughout storage. Results indicated that the combined $CaCl_2$–GA treatment was the most effective in reducing visual deterioration and preserving firmness in both peel and pulp from week 2 onward compared to the control. Coated fruits exhibited slower changes in pH, SSC and titratable acidity, indicating suppressed metabolic activity. The uncoated fruits initially showed the highest antioxidant activity and phenolic content, but these values declined rapidly during storage. In contrast, coated fruits maintained -more stable antioxidant properties over time. The $CaCl_2$–GA treatment extended the marketable shelf life of tarap fruit from approximately 7 days in uncoated fruit to 21 days under cold storage conditions. These findings suggest that the $CaCl_2$-GA composite coating synergistically enhances the postharvest quality, textural integrity and antioxidant stability of tarap fruit under cold storage, highlighting its potential as a sustainable and practical postharvest preservation strategy.

Keywords: antioxidant activity, calcium chloride, cold storage, fruit firmness, gum arabic coating, tarap fruit

1. INTRODUCTION

Artocarpus odoratissimus, commonly known as tarap, is a tropical fruit native to Borneo and the Mindanao region. It thrives at altitudes of up to 1000 meters in humid and warm climates [1]. Belonging to the same genus as jackfruit and breadfruit, tarap is distinguished by its strong durian-like aroma and significant nutritional value. The fruit is rich in phenolic and flavonoid compounds that offer antioxidant, anticancer and anti-inflammatory properties [2]. Economically versatile, its sweet pulp is consumed fresh or processed into various products, while the peel has been used in the green synthesis of gold nanoparticles highlighting its potential in both traditional and modern applications [2,3]. Precise production and consumption data for *A. odoratissimus* remain unavailable, highlighting a critical knowledge gap for this indigenous tropical fruit. However, experimental postharvest studies provide quantitative evidence of its high perishability under ambient storage at 25°C, tarap fruits lost approximately 12.20% of fresh weight by day 4 and 11.09% by day 8, reflecting rapid moisture loss and quality deterioration that contribute to postharvest losses and reduced marketability [4].

Despite its potential, postharvest handling of *A. odoratissimus* remains a significant challenge with spoilage and quality deterioration that limiting its commercial viability [4]. This fruit often undergoes flavour loss, tissue pulp softening, and surface browning due to improper postharvest handling [5]. Various methods for improvement need to be identified such as refrigeration, chemical treatments and advanced physical interventions like heat shock, high-pressure processing and pulsed-electric-field treatments to extend fruit shelf life. However, these approaches often present limitations including quality degradation and potential health concerns [6,7,8]. For example, the application of chemical preservatives such as sulphur dioxide, benomyl and methyl jasmonate may inhibit spoilage but can adversely affect sensory qualities and introduce health risks at high concentrations [9,10].

Current postharvest handling practices for tarap are largely unstandardized contributing to rapid spoilage and reduce shelf life [11]. Additionally, there is a lack of detailed studies on controlled ripening and the influence of temperature management during storage and transportation particularly in rural areas of Borneo where cold-chain infrastructure is limited. Recent reviews emphasize that lab-based emerging technologies such as edible coatings have demonstrated promising results in extending the shelf life of various tropical fruits [12]. Edible coatings act by forming a thin, semi-permeable layer on the fruit surface, which modulates moisture loss and gas exchange, reduces respiration and metabolic rates, and can serve as a carrier for bioactive compounds to enhance antioxidant and antimicrobial defenses [13,14]. This combined action effectively delays senescence and helps maintain the physico-chemical and nutritional quality of fruits during storage. Polysaccharide-based coatings, including chitosan, carboxymethyl cellulose and gum arabic, have been widely reported to reduce postharvest deterioration, inhibit microbial growth and extend the shelf life of fresh produce under both ambient and cold storage conditions (Shakir et al., 2022; Aparna and Geetha, 2024). However, their application remains largely untested on tarap fruit. According to studies by [15] and [16], edible coating technology offers several advantages in postharvest management. Through forming a semi-permeable barrier on the fruit surface, these coatings reduce moisture loss, limit gas exchange and slow down metabolic processes thereby delaying deterioration and prolonging fruit shelf life.

Among promising coating agents, calcium chloride ($CaCl_2$) and gum arabic (GA) have shown effectiveness in several fruits. [17] reported that postharvest application of calcium chloride on fresh strawberries provides several key benefits for preserving its quality, primarily by reducing physiological weight loss during storage compared to untreated controls. Calcium ions stabilize cell membranes and interact with pectin to enhance cell wall integrity and turgor in fresh strawberries, thereby slowing their respiration and transpiration rates [18]. Similarly, GA has gained interest as an effective edible coating material in postharvest management. According to [19], persimmon fruits coated with 10% GA retained higher firmness and biochemical quality during ambient storage due to reduced weight loss, membrane leakage, hydrogen peroxide levels and malondialdehyde accumulation compared to uncoated fruits. [20] further demonstrated that 12 to 15% GA coatings on Ponkan citrus fruits significantly preserved total soluble solids, titratable acidity and suppressed oxidative stress markers by maintaining antioxidant enzyme activity in the fruits for up to 120 days under cold storage.

Although direct studies on tarap fruits are limited, the combined application of $CaCl_2$ and GA could synergistically enhance their postharvest preservation through the application of this sustainable and biodegradable coatings. The $CaCl_2$-GA composite treatment has the potential to enhance overall quality retention and nutritional stability in this underutilised tropical fruit. Previous studies demonstrated that $CaCl_2$ and GA coating reduced enzymatic browning by limiting oxygen permeability and preserving membrane integrity, leading to lowering PPO enzyme activity in tropical fruits such as blueberries [21], avocado [22], mango [23], apples [24] and peach fruits [25]. These effects contribute to delayed senescence and improve postharvest quality of fruit during storage.

The present study aims to evaluate the effectiveness of $CaCl_2$ and GA coatings in retaining the physico-chemical and antioxidant properties of *A. odoratissimus* during refrigerated storage at 10°C (85-90% RH) over a three-week period. This study supports the preservation of this highly perishable fruit and contributes to the development of safe, low-cost and sustainable practices that enable extended storage and distribution of *A. odoratissimus* fruit.

2. MATERIALS AND METHODS

2.1 Fruit Materials

Mature stage of *Artocarpus odoratissimus* (tarap) fruits were obtained from a commercial plantation located in Bekenu, Miri, Sarawak (4.0582° N, 113.8442° E) during the peak fruiting season between August and September 2024. Fruit samples were harvested in the morning and transported immediately in an air-conditioned vehicle on the same day to the Postharvest Laboratory at Universiti Putra Malaysia Sarawak. Only fruit of uniform size (700 g to 1 kg per fruit), shape, maturity and free from pests, diseases and physical injuries were selected for the study.

2.2 Preparation of Coating Solutions and Application of Treatments

Food-grade of calcium chloride ($CaCl_2$) and gum arabic (GA) were purchased from Sigma Chemical Co., USA. A 3% (w/v) $CaCl_2$ solution was prepared by dissolving 3 g of calcium chloride in distilled water, followed by constant agitation using a magnetic stirrer for 30 min. To improve wettability, 0.2 mL of Tween 20 (polyoxyethylene sorbitan monoleate, Sigma Aldrich) was added during mixing. Separately, a 5% (w/v) GA solution was prepared by dissolving 10 g of GA in distilled water. The mixture was stirred and heated on a hot plate at 40°C for 60 min to ensure complete dissolution. Glycerol (1%, v/v) was added to both solutions as a plasticizer. The pH of each solution was adjusted to 5.6 using 1 mol L^{-1} sodium hydroxide (NaOH) monitored with a pH meter. For the combined treatment, equal volumes (1:1) of the 3% $CaCl_2$ and 5% GA solutions were mixed and stirred for 30 min after pH adjustment to 5.6. Four coating treatments were prepared for the study: (1) sterilized distilled water as control, (2) 3% $CaCl_2$, (3) 5% GA and (4) 3% $CaCl_2$ + 5% GA. Prior to coating, all fruits were sanitized by immersion in a 0.01% sodium hypochlorite solution for 2 min, followed by rinsing twice with sterile distilled water to remove residual bleaching agent. The fruits were then air-dried at room temperature (25±2°C, 85-90% RH) for 1 h.

The concentrations of $CaCl_2$ (3%) and GA (5%) were selected based on prior optimization studies demonstrating their effectiveness in preserving fruit quality without causing undesirable effects on tarap fruit. Moderate $CaCl_2$ concentrations around 3% have been shown to reduce weight loss, maintain firmness and improve overall quality in treated fruit when applied alone or in combination with edible coatings [26].

The fruits were randomly divided into four groups, with each group containing eight tarap fruits (4 storage intervals x 2 replicates). Each group was dipped into one of the coating solutions for treatment. The control group was dipped in sterilized distilled water containing Tween 20. Following coating, all fruits were air-dried for 1 h and then individually wrapped using shrink film (0.02 mm thickness) to maintain a relative humidity of approximately above 85% during refrigerated storage. All samples were stored at 10°C for 3 weeks. Data were collected at four storage intervals: weeks 0, 1, 2 and 3 during storage. Eight fruits were sampled per week, resulting in a total of 32 fruit samples (4 treatments x 4 storage weeks x 2 replicates).

2.3 Determination of Peel and Pulp Colour

Peel colour was measured at five regions on the surface of each tarap fruit including the stem end, equatorial region and floral end by using a colorimeter equipped with an 8 mm diameter measuring head and a standard calibration tile. Calibration values were L* = 97.30, C* = 1.88 and h° = 85.8 using Illuminate C as the light source [27]. After colour measurements, the fruit was peeled and colour parameters were recorded from five individual pulp segments of tarap fruit. Peel and pulp colours were expressed in terms of L* (lightness), C* (chroma) and h° (hue angle) values.

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2.4 Determination of Peel and Pulp Firmness

Peel and pulp firmness were measured using a handheld penetrometer. Firmness was recorded in Newtons (N) by taking five readings per fruit. For peel firmness, measurements were taken at five distinct points throughout the surface area of the fruit which includes the stem end, equatorial region and floral end. For pulp firmness, measurement taken from five randomly selected pulp segments per fruit.

2.5 Determination of Titratable Acidity (TA)

Titratable acidity (TA) was determined following the method described by [28]. Ten grams of tarap pulp were homogenised with 40 mL of distilled water using a kitchen blender (MX-900M, Panasonic, Malaysia) for 1 min. The homogenate was filtered through cotton wool placed in a funnel. A 5 mL aliquot of the filtrate was transferred into a 100 mL conical flask, followed by the addition of three drops of 1% (v/v) phenolphthalein indicator. The sample was titrated with 0.1 M sodium hydroxide (NaOH) until a persistent light pink colour appeared and held for at least 15 s. The titre volume was recorded and the results were expressed as percentage of anhydrous malic acid (%).

2.6 Determination of Soluble Solids Concentration (SSC)

The SSC of tarap fruit pulp was determined using a digital refractometer (Model N-1 α Atago, Japan). The filtered juice obtained from the titratable acidity determination was used for this measurement. Two drops of the filtrate were placed on the clean prism of the refractometer using a plastic dropper. Readings were recorded and multiplied by a dilution factor of 5 to express the SSC as percentage (%SSC).

2.7 Determination of pH

The remainder of filtrates from SSC determination was used to measure pH of the fruit pulp using a calibrated glass electrode pH meter (Crison Instruments, S.A., Barcelona). The electrode was rinsed with distilled water between readings. The pH was measured by immersing the electrode in the filtrate and recording the value once it stabilized.

2.8 Ascorbic Acid Determination

The quantification of ascorbic acid in tarap was carried out following the method described by [28]. Approximately 10 g of tarap pulp was homogenized with 100 ml of 3% (w/v) oxalic acid using a food processor (Mr. DIY). The homogenate was then filtered through cotton wool placed in a filter funnel to obtain a clear extract. A 5 mL aliquot of the extract was titrated against a dye solution of 2,6-dichlorophenolindophenol until a light pink colour persisted for at least 20 s. The ascorbic acid content was calculated using L-ascorbic acid as the reference standard and the results were expressed in mg per 100 g fresh weight (FW). A standard calibration curve of L-ascorbic acid was prepared in the range of 0–50 μg mL^{-1}, with a coefficient of determination (R^2) greater than 0.99.

2.9 Sample Extraction

The extraction of total phenolic contents and antioxidant activities from tarap fruit pulp was conducted following the method described by [29] with slight modifications. Approximately 20 g of pulp tissue from each sample was homogenized using a mortar and pestle, then stored at -20°C until further use. For extraction, 0.1 g of frozen pulp was mixed with 10 mL of 80% methanol and shaken at 200 rpm for 2 h at room temperature using an orbital shaker [30]. The extract was centrifuged at 2000 rpm for 10 min and the supernatant was filtered through Whatman filter paper. The resulting filtrate was stored at -20°C prior to analysis of total phenolic content and antioxidant activity.

2.10 Total Phenolic Content Determination

Total phenolic content was determined using the Folin-Ciocalteu reagent [30] with minor modifications. Briefly, 300 μL of the extract was added to 2250 μL of 10-fold diluted Folin-Ciocalteu reagent and vortexed for 15 s. After standing at room temperature for 5 min, 2250 μL of sodium carbonate solution (60 g/L) was added. The mixture was then incubated at room temperature for 90 min. Absorbance was measured at 725 nm using a UV-Vis spectrophotometer. Gallic acid was used as the standard (0 - 100 μg/mL) and results were expressed as mg gallic acid equivalents per 100 g of fresh weight (mg GAE/100 g FW).

2.11 Antioxidant Activity Determination

The antioxidant activity was assessed using the DPPH (2,2-diphenyl-1-picrylhydrazyl) free radical scavenging assay as described by [30]. A 0.1 mL aliquot of the extract was mixed with 3.9 mL of 1 mM methanolic DPPH solution, vortexed and left to stand in the dark at room temperature for 30 min. Absorbance was measured at 517 nm. A control was prepared by replacing the extract with 0.1 mL of 80% methanol. The antioxidant activity was expressed as the percentage of DPPH radical inhibition [31].

ABTS radical scavenging activity was determined according to [32]. Equal volumes of 7 mM ABTS and 2.45 mM potassium persulfate solutions were mixed and incubated in the dark at room temperature for 12 to 16 h to generate the $ABTS^{\cdot +}$ radical cations. The stock solution was then diluted with 80% methanol to an absorbance of 0.700 ± 0.020 at 734 nm. A 3 mL aliquot of the diluted ABTS solution was mixed with 100 µL of the sample extract and vortex mixed. After 10 min of incubation at room temperature, absorbance was measured at 734 nm. The control was prepared by replacing the extract with 100 µL of 80% methanol. The results were expressed as the percentage inhibition of ABTS [31].

The FRAP assay was conducted according to the method of [33] with slight modifications. The FRAP reagent was freshly prepared by mixing 20 mM ferric chloride, 0.3 M acetate buffer (pH 3.6) and 10 mM TPTZ solution (in 40 mM HCl) in a 1:10:1 (v/v/v) ratio. For the assay, 40 µL of the extract was added to 3 mL of the FRAP reagent and incubated in a water bath at 37 °C for 1 h. Absorbance was measured at 593 nm. A control was prepared by mixing 40 µL of 80% methanol with 3 mL of FRAP reagent. Trolox was used to generate the standard curve (200 - 1000 µg/mL) and results were expressed as µmol Trolox equivalent (TE) per 100 g fresh weight (FW).

2.12 Statistical Analysis

The experiment was conducted using a completely randomized design (CRD) with a two-factorial arrangement. The two factors were coating treatment and storage durations with four levels, respectively. Each treatment combination was applied to two biological replicates, from which three subsamples were obtained. All measurements for each subsample were conducted in triplicate to minimize technical variability. Data were subjected to one-way analysis of variance (ANOVA) and treatment means showing significant differences were compared using Duncan's Multiple Range Test (DMRT) at a significance level of $P \leq 0.05$. All statistical analyses were performed using SAS software version 9.4 (SAS Institute Inc., Cary, NC, USA).

3. RESULTS AND DISCUSSION

3.1 Effects of Gum Arabic and Calcium Chloride Coatings on Physical Characteristics of Tarap Fruit

The progressive changes in the visual appearance of cold-stored tarap fruits subjected to four different coating treatments was shown in Figure 1. At w 0, all fruits exhibited a uniformly fresh appearance with minimal external browning discoloration. As storage progressed to w 3, differences in visual deterioration became increasingly evident among treatments. The control group which was dipped with sterile distilled water showed the most pronounced browning, desiccation and shriveling by the end of w 3. In contrast, fruits coated with the combined treatment (3% calcium chloride + 5% gum arabic) exhibited reduced browning and maintained better turgidity. Meanwhile, tarap fruits treated with either calcium chloride ($CaCl_2$) or gum arabic (GA) individually appeared moderately better in visual quality than the uncoated fruit.

The rapid visual deterioration in the control fruit can be attributed to moisture loss, oxidative stress and enzymatic browning which were common in uncoated fruit [34]. Whereas the superior visual quality that was observed on fruits coated with GA supports findings by [35] and [36], who reported that GA as edible coating can act as semi-permeable barriers to gases and moisture thereby reducing respiration and desiccation processes. $CaCl_2$ has also been shown to reinforce fruit cell walls and delay ripening by stabilizing membrane structures [37]. When $CaCl_2$ at 2% (w/v) was combined with edible coating such as alginate, a synergistic effect has been observed further extending shelf life by maintaining firmness and visual quality in fresh-cut apples [38]. Alginate coating applications in fresh-cut pineapple coatings also reduced juice leakage and helped preserve fruit texture [39]. Comparable improvements in visual quality, firmness retention and delayed senesecence have also been reported in other tropical and subtropical fruits subjected to edible coatings treatments. For instance, mango fruit coated with polysaccharide-based films such as chitosan exhibited delayed softening and reduced quality deterioration during storage, demonstrating preserved firmness and appearance [36, 40]. Comprehensive reviews of edible coatings further confirm that such treatments consistently extend shelf life and maintain sensory and physico-chemical quality across diverse fruits, including mango, guava and other climacteric species by regulating moisture and gas exchange and slowing physiological degradation [13,14]. These findings highlight the broader applicability of calcium-polysaccharide composite coatings and support the present results observed in tarap fruit.

Colour characteristics of tarap fruit peel and pulp particularly lightness (L*), chroma (C*) and hue angle (h°) are crucial indicators of postharvest quality and strongly influence consumer acceptance. Among the coating treatments, significant differences were observed in both peel and pulp L* (Table 1). Uncoated tarap fruits recorded the highest

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peel L* value (24.91) and the lowest pulp L* (46.59), indicating darker internal pulp tissues despite brighter outer fruit surfaces. In contrast, fruits coated with 5% GA had the lowest peel L* (18.51) but the highest pulp L* (56.05), suggesting improved preservation of internal color. These differences may be related to the nature of hydrocolloid coatings, which alter surface reflectance and initially appear darker due to film deposition [41]. However, a significant interaction effect (CT × SW: $p \leq 0.001$) indicated variability over time, consistent with the trend in Figure 2, where GA-treated fruit exhibited an increase in peel lightness, reaching a comparable high value of 23.51 by w 3. This suggests GA may initially reduce lightness but more effectively preserves peel color during storage by acting as an oxygen barrier and reducing oxidative browning [42,20]. In contrast, the combined treatment (3% $CaCl_2$ + 5% GA) experienced a steep decline in peel lightness, dropping to an L* value of 14 by w 3, which was lower than uncoated fruits (Figure 2). This result may indicate a potential incompatibility in the combined coating matrix and excessive moisture retention under dual layers which could favor pigment degradation in the fruit peel [43].

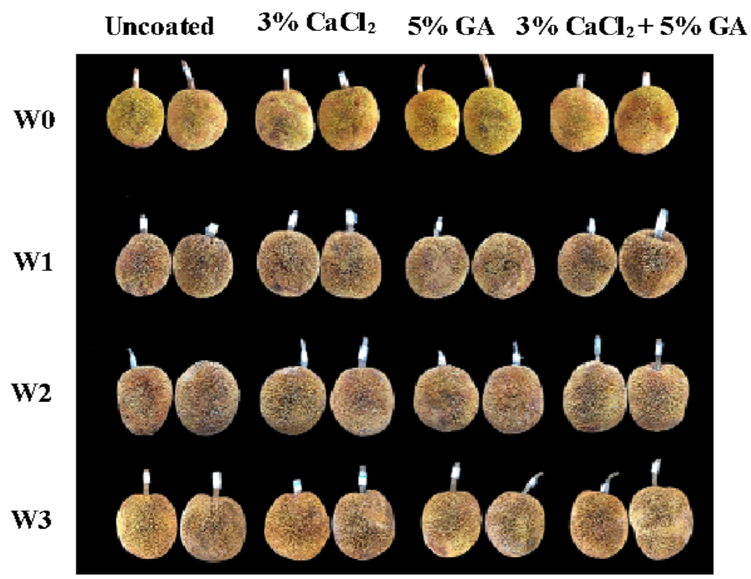

Figure 1. Visual appearance of uncoated (control), 3% calcium chloride, 5% gum arabic and 3% calcium chloride + 5% gum arabic tarap fruits during storage at 10°C (85-90% RH) for 3 weeks.

Table 1. Main and interaction effects of different coating treatments and storage weeks on peel and pulp lightness (L*), chroma (C*) and hue (h°) of tarap fruit stored under cold storage at 10°C and 85-90% relative humidity.

Factors	Peel			Pulp		
	L*	C*	h°	L*	C*	h°
Coating treatments (CT)						
Uncoated	24.91 a[z]	43.78 c	17.14 ab	46.59 b	16.03 a	21.92 a
3% calcium chloride ($CaCl_2$)	21.55 b	49.03 ab	16.94 ab	52.00 a	14.80 a	19.43 ab
5% gum arabic	18.51 c	52.76 a	16.13 b	56.05 a	16.47 a	17.51 b
3% $CaCl_2$ + 5% gum arabic	22.30 b	47.18 bc	18.13 a	53.37 a	15.47 a	17.31 b
Storage week (SW)						
0	23.87 a	49.56 a	16.22 a	53.18 c	16.37 a	23.14 a
1	23.87 a	49.56 a	16.22 a	30.66 d	16.70 a	17.50 b
2	19.56 b	49.00 a	18.01 a	58.37 b	15.98 a	18.57 b
3	19.97 b	44.63 b	17.91 a	65.80 a	13.70 a	16.96 b
Interactions						
CT x SW	***	ns	ns	*	ns	ns

[z] Means followed by the same letter in the same column within factors are not significantly different at $P \leq 0.05$ according to Duncan's multiple range test.
*, ***, ns Significant difference at $P \leq 0.05$, $P \leq 0.001$ or not significant difference at $P > 0.05$.

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In terms of pulp lightness (Figure 3), fruit treated with either 5% GA alone or in combination with 3% $CaCl_2$ retained significantly higher pulp lightness values ranging from 33.88 to 42.44 by w 1. In contrast, the untreated control showed a markedly lower pulp lightness value of 19.92. However, as storage progressed to w 3, no significant differences in pulp lightness were observed among the treatments. These findings align with previous studies on other fruits, where GA coatings were shown to delay browning in bananas while $CaCl_2$ treatments contributed to maintaining firmness and internal colour [44]. Similarly, studies on mangoes and guavas have demonstrated that combining $CaCl_2$ and edible coatings can effectively delay senescence and enzymatic browning [45].

Neither treatment nor storage weeks significantly affected peel or pulp chroma (C*) and hue (h°) (Table 1). This suggests that the coating treatments primarily influenced fruit lightness, while the colour saturation (chroma) and tint (hue) of tarap fruit remained relatively stable throughout the storage weeks. However, fruits treated with 5% GA tended to exhibit slightly higher peel chroma (52.76) compared to uncoated fruits while maintaining stable hue values (6.47) (Table 1). These results indicate improved retention of visual colour intensity in GA-coated fruits. This observation agrees with previous finding showing that GA coatings can delay color changes and maintain visual quality in various fruits during cold storage, including bananas [48], apples [47], blueberries [21], mangoes [23] and avocados [48]. Meanwhile, pulp hue values showed a slight decrease over the storage period, from 21.92 at w 0 to 16.96 at w 3 (Table 1), indicating a shift in perceived colour possibly due to pigment oxidation as tarap fruit progressed in ripening.

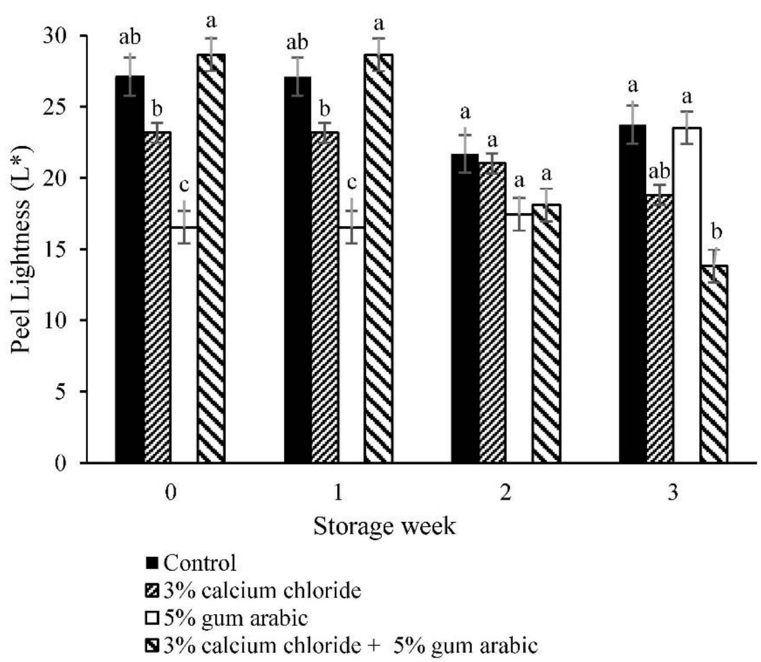

Figure 2. Effect of different coating treatments on peel lightness (L*) of tarap fruit stored at 10°C and 85-90% relative humidity for 3 storage weeks. Different letters in each storage week are significantly different at P≤0.05 according to Duncan's multiple range test.

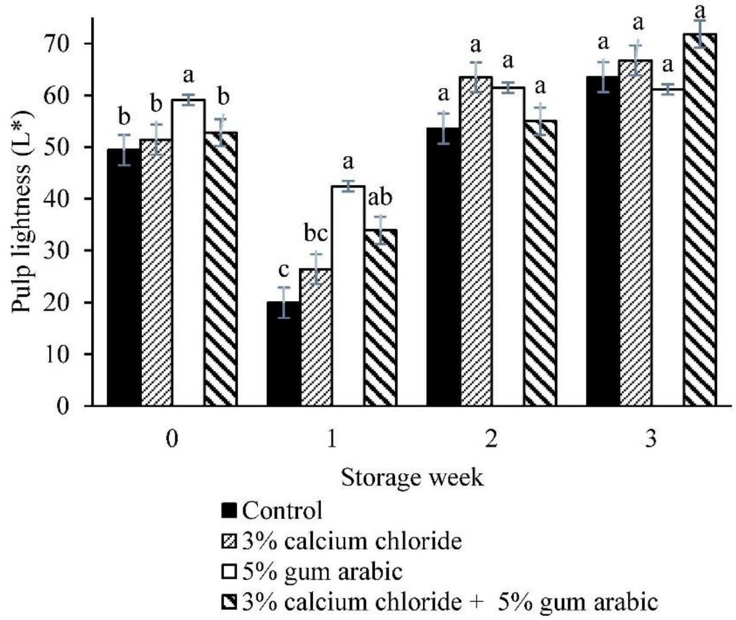

Figure 3. Effect of different coating treatments on pulp lightness (L*) of tarap fruit stored at 10°C and 85-90% relative humidity for 3 storage weeks. Different letters in each treatment are significantly different at P≤0.05 according to Duncan's multiple range test.

Firmness is another critical indicator of fruit quality as it directly reflects the physical texture and the fruit's resistance to mechanical damage during handling and storage. Figure 4 and 5 illustrate the changes in peel and pulp firmness of tarap fruit subjected to different postharvest coating treatments and stored at 10°C (85-90% RH) for three weeks. Fruits treated with 3% $CaCl_2$ either alone or in combination with 5% GA consistently maintained significantly higher peel firmness (P≤0.05) from w 1 to w 2 of storage compared to the uncoated and GA-alone treatments (Figure 4). In contrast, the control group exhibited a rapid decline in peel firmness as early as w 1, indicating advanced softening and senescence. These findings align with previous research showing that calcium ions from $CaCl_2$ solutions were important to stabilize fruit cell walls and membranes by cross-linking with pectic substances in the middle lamellae [49,50, 37]. While GA coating alone moderately delayed peel firmness loss in tarap fruits due to its semi-permeable properties that restrict gas exchange and reduce water loss [51], thus it was less effective than $CaCl_2$. However, through combining $CaCl_2$ with GA, these coating appeared to synergise the effect between calcium-induced cell wall fortification and moisture-retaining semi-permeable barrier properties of GA [36,46]. These results are consistent with previous studies on mango which reported that combining calcium salts and polysaccharide edible coatings effectively maintained textural quality during storage [23,52].

Although sensory attributes were not directly measured in the present study, edible coatings are known to influence fruit flavour and aroma by altering respiration, moisture loss and volatile compound dynamics during storage. Natural edible coatings often act as mild semi-permeable barriers that slow down oxidative changes and moisture loss, helping preserve the sensory characteristics of coated fruits without introducing off-flavours or undesirable tastes [12]. This suggests that coatings like GA and $CaCl_2$ applied to tarap may help maintain its intrinsic balance of sweetness and aroma by moderating metabolic changes associated with ripening.

Evidence from other tropical and climacteric fruits supports this interpretation. In mango (*Mangifera indica*), GA coating combined with $CaCl_2$ was reported to delay ripening, suppress respiration and ethylene production and maintain higher titratable acidity and ascorbic acid during low-temperature storage, factors closely linked to the preservation of fresh taste and aroma [23]. Similar effects have been observed in other horticultural commodities. In tomatoes and other horticultural crops, application of natural gum-based coatings preserved aroma quality by limiting moisture sensory appeal [54]. Similarly, research on guava coated with a gum arabic-beeswax-coconut oil formulation reported that coated fruits exhibited delayed ripening and different sensory acceptability scores compared to uncoated controls, indicating that coating composition and ripening dynamics can influence taste and aroma perception [55].

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In terms of pulp firmness of tarap fruit (Figure 5), results showed a sharp decline in firmness in the control group during weeks 1 and 2, reaching values as low as 6.08-7.39 N, indicating rapid pulp softening. In contrast, fruits treated with 3% $CaCl_2$ either alone or in combination with 5% GA maintained significantly higher pulp firmness by the end of the storage period with values ranging from 34.15 to 34.29 N. The firmness-preserving effect of $CaCl_2$ can be attributed to its ability to inhibit cell wall degrading enzymes such as polygalacturonase (PG) and pectin methyl esterase (PME), which are primarily responsible for pulp softening and fruit senescence. This mechanism is supported by previous studies on $CaCl_2$-treated red raspberries and *Ber* fruits, where treatments suppressed PG and PME activities while conserving protopectin, cellulose and other structural polysaccharides during storage [53,56]. Interestingly, fruits treated with 5% GA alone exhibited a unique trend with a marked increase in pulp firmness from 18.49 at w 0 to 33.9 N at w 1. This increase may be attributed to reduced metabolic activity possibly associated with a lower respiration rate and suppressed ethylene activity induced by the application of plant-based gums [51]. Similar findings have been reported in previous studies, where GA-coated blueberries and persimmons maintained higher firmness through the inhibition of pectin degradation and delayed softening [21,58]. However, this firmness-enhancing effect appeared to diminish by w 3, at which point GA-treated fruits were significantly softer than those treated with calcium-based coatings or the controls (Figure 5). The consistent firmness observed in the combined treatment (3% $CaCl_2$ + 5% GA) suggests a possible synergistic effect between calcium ions and polysaccharide matrix as previously reported in Choke Anan mango during cold storage [23]. Thus, treatment with 3% $CaCl_2$ either alone or in combination with GA was highly effective in preserving both peel and pulp texture and in delaying ripening of tarap fruit under low temperature storage.

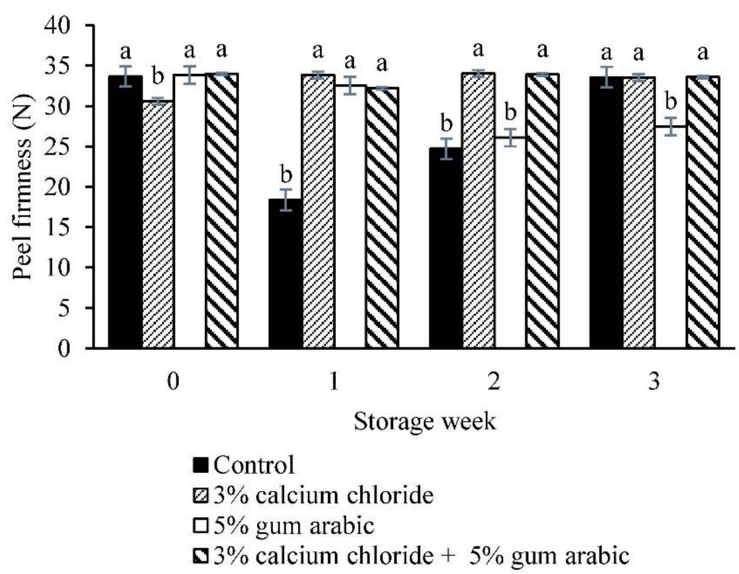

Figure 4. Effect of different coating treatments on peel firmness of tarap fruit stored at 10°C and 85-90% relative humidity for 3 storage weeks. Different letters in each treatment are significantly different at P≤0.05 according to Duncan's multiple range test.

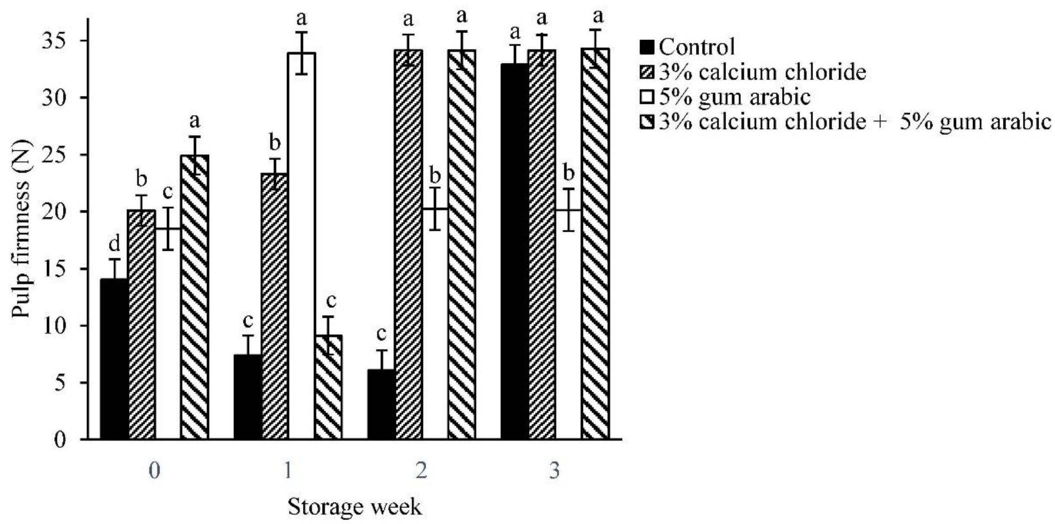

Figure 5. Effect of different coating treatments on pulp firmness of tarap fruit stored at 10°C and 85-90% relative humidity for 3 storage weeks. Different letters in each treatment are significantly different at P≤0.05 according to Duncan's multiple range test.

3.2 Effects of Gum Arabic and Calcium Chloride Coatings on Chemical Characteristics of Tarap Fruit

The pH of tarap fruit was significantly affected by both coating treatments and storage duration (Figure 6). At the initial storage, all treatments showed relatively similar pH values ranging from 5.26 to 5.63. As storage progressed to w 1, a general increase in pH was observed in all treatments, however, the differences were not statistically significant. In w 2, a decline in pulp pH was recorded with the most prominent reduction seen in the 5% GA treatment, which dropped to pH 5.16 (Figure 6). In contrast, the slower decline in control and 3% $CaCl_2$-treated fruits suggested a delay in the ripening process and organic acid metabolism. This observation aligns with findings in apples fruit where postharvest calcium treatments were shown to increase membrane integrity within the tissue thereby delaying senescence and reducing physiological disorders [59]. Similarly, calcium-treated apples exhibited increased fluidity and structural rigidity particularly at the membrane surface as evidenced by fluorescence polarization analysis [60]. By the end of storage period, no significant differences in pH were observed among treatments, indicating that the coatings did not have a lasting effect on the fruit acidity and sourness under low temperature storage.

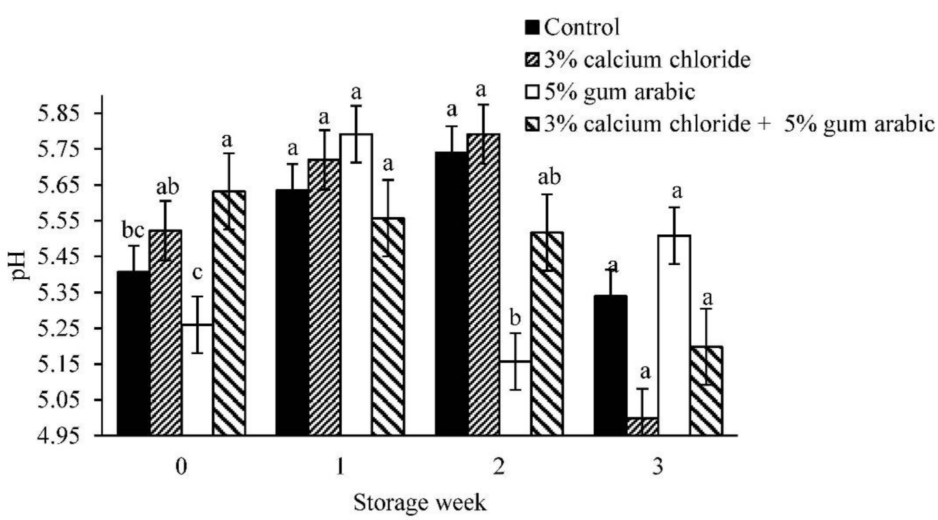

Figure 6. Effect of different coating treatments on pH of tarap fruit stored at 10°C and 85-90% relative humidity for 3 storage weeks. Different letters in each treatment are significantly different at P≤0.05 according to Duncan's multiple range test.

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Soluble solids concentration (SSC) is mainly influenced by water loss, respiration rate and carbohydrate metabolism in fruit during storage [61]. At the beginning of storage, all treatments exhibited SSC values ranging from 3.9 to 6%, except for 5% GA treatment, which showed the lowest initial SSC at 1.5% (Figure 7). Throughout storage, control fruits exhibited the most pronounced increase in SSC, peaking at 11.08% by w 2. This trend suggests accelerated ripening and sugar accumulation in uncoated tarap fruits. In contrast, all coatings treatments applied resulted in significantly lower SSC increases during the same period, indicating a delay in ripening and sugar conversion process. These findings aligned with previous studies reporting that calcium chloride ($CaCl_2$) treatments slowed metabolic activity and respiration rate in strawberries [18] and red raspberries [54], thereby retarding sugar synthesis and ripening process. Similarly, [47] found that Anna apple coated with arabic gum showed a significant delay in the increase of total soluble solids during cold storage at 0°C and 90-95% RH compared to uncoated apples. By w 3, SSC in control fruits declined mainly due to transpiration and sugar degradation associated with fruit senescence (Figure 7). In contrast, 5% GA-coated fruits maintained a high SSC (10.67%) potentially due to reduced sugar degradation and delayed senescence provided by the semi-permeable barrier properties of gum arabic (GA). Interestingly, tarap fruits coated with the combination of 3% $CaCl_2$ and 5% GA demonstrated a delayed but steady sugar release pattern throughout the cold storage period (Figure 7). A similar synergistic effect was observed in bananas coated with a composite of 10% GA and 1% chitosan, which significantly delayed increases in SSC changes during storage at 13 ± 1 °C for 28-33 days, further supporting the potential of such combinations in slowing the ripening process [46].

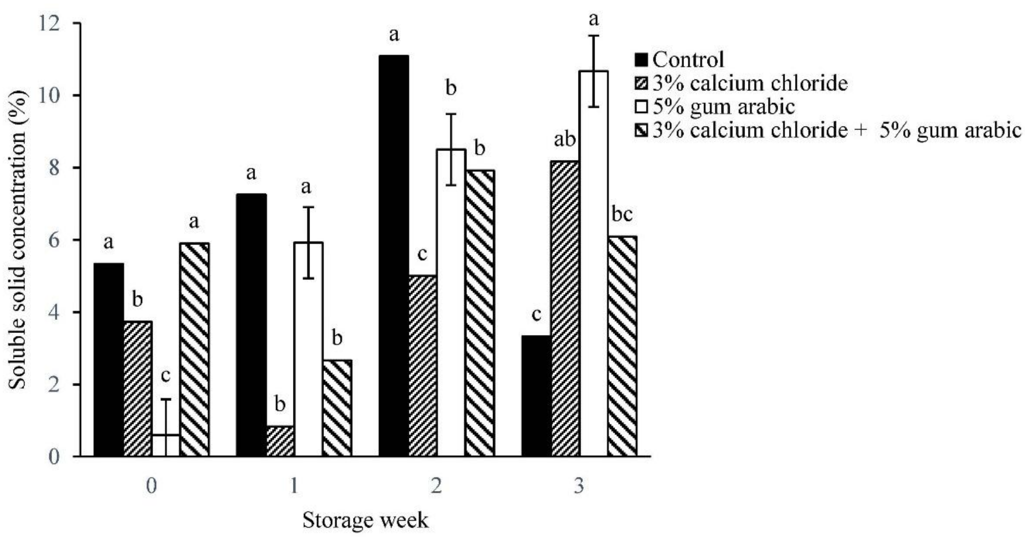

Figure 7. Effect of different coating treatments on SSC of tarap fruit stored at 10°C and 85-90% relative humidity for 3 storage weeks. Different letters in each treatment are significantly different at P≤0.05 according to Duncan's multiple range test.

Figure 8 presents the changes in titratable acidity and expressed in malic acid percentage (%) of tarap fruit subjected to different postharvest coatings during 3 weeks of cold storage. At the beginning of storage, all fruits exhibited low initial acidity levels (0.03-0.05%). As storage progressed, titratable acidity was increased across all treatments particularly in coated fruits, indicating the organic acids accumulated during advanced ripening stages. By w 2, uncoated tarap fruits showed a sharp increase, peaking at 0.32% while 3% $CaCl_2$, 5% and their combination treatment exhibited more gradual increases. At the end of storage duration, the highest malic acid content was recorded in tarap fruits coated with 5% GA (0.38%) and 3% $CaCl_2$ + 5% GA (0.36%), followed by 3% $CaCl_2$ alone (0.31%) where all of which were significantly higher ($P<0.05$) than the control (0.25%). The elevated in malic acid suggested the reduced in metabolic activity particularly in fruit respiration rate that imposed by both coating applications. The semi-permeable barrier that formed by GA, particularly might reduce oxygen availability and minimize oxidative catabolism of organic acids in fruit [62]. [63] was also reported the delay in acid loss in mango fruits after coating with mango carnauba (1:1 v/v). In contrast, the significant decline of acidity in uncoated tarap fruits might reflect the onset of senescence and rapid organic acid utilisation as substrates during ripening [64].

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Initial ascorbic acid content in tarap fruit pulp was relatively low across all treatments, ranging from 7.30 to 10.94 mg/100 g of fruit fresh weight (FW) (Figure 9). During storage, ascorbic acid levels increased progressively particularly in fruits treated with 3% $CaCl_2$, which exhibited the highest concentration by w 2 (26.57 mg/100 g FW). This trend suggests that $CaCl_2$ might have played a role in delaying the oxidative degradation of ascorbic acid. In contrast, the lower ascorbic acid content observed in control fruits might reflect higher rates of oxidative loss due to reduced structural protection of fruit tissue. According to [65,66], $CaCl_2$ treatment was effective in enhancing the structural integrity of litchi fruit cell walls, thereby reducing ascorbate oxidase activity and limiting oxidative stress. Similarly, [67] demonstrated that $CaCl_2$ was a powerful strategy for maintaining higher levels of anthocyanins, flavonoids, ascorbic acid and total antioxidant capacity in cornelian cherry fruit.

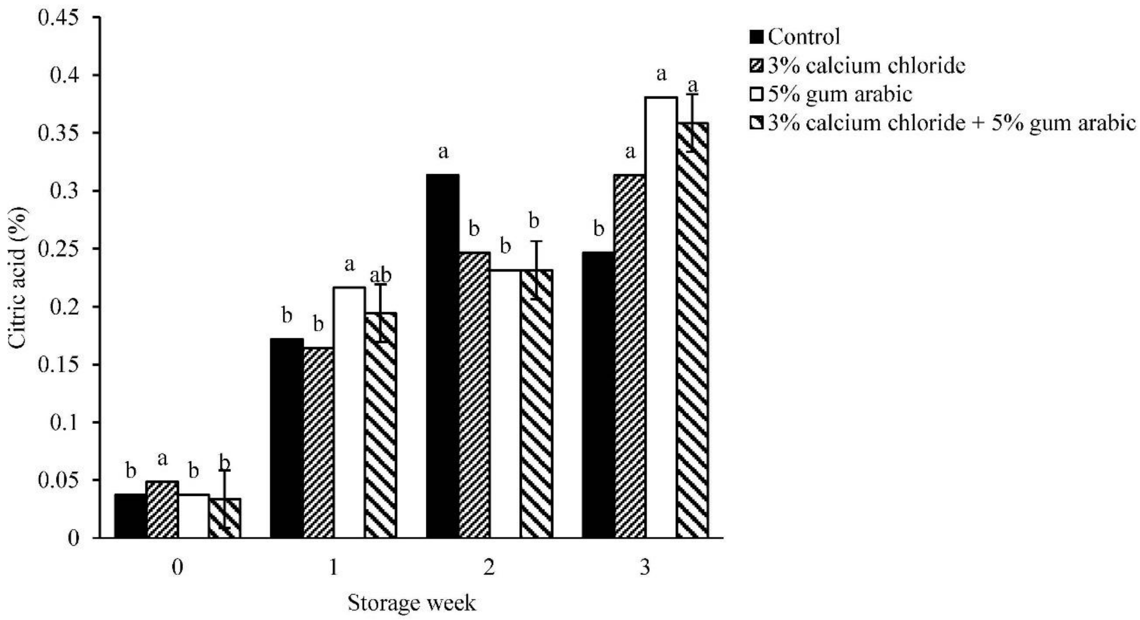

Figure 8. Effect of different coating treatments on titratable acidity of tarap fruit stored at 10°C and 85-90% relative humidity for 3 storage weeks. Different letters in each treatment are significantly different at P≤0.05 according to Duncan's multiple range test.

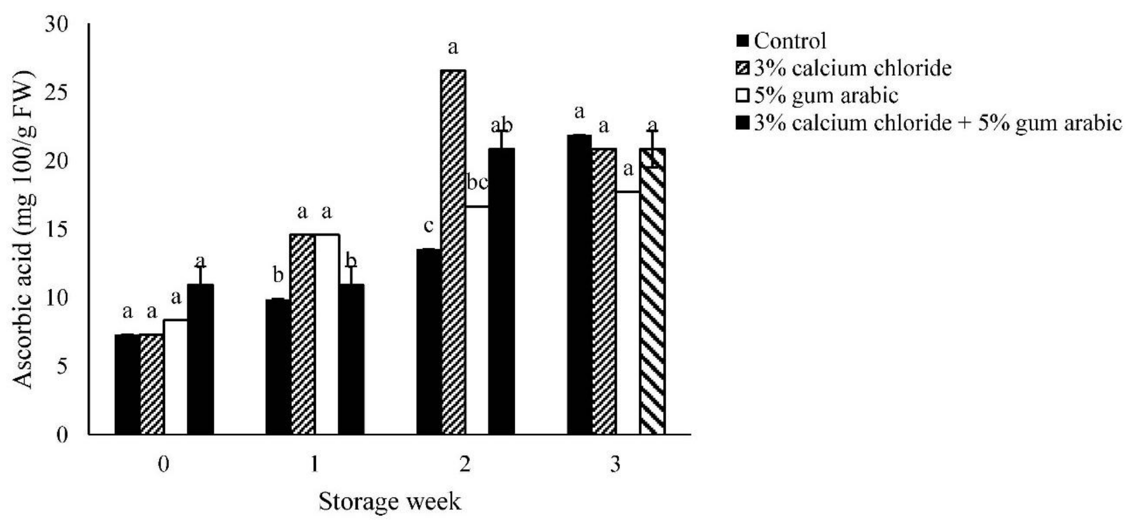

Figure 9. Effect of different coating treatments on ascrbic acid of tarap fruit stored at 10°C and 85-90% relative humidity for 3 storage weeks. Different letters in each treatment are significantly different at P≤0.05 according to Duncan's multiple range test.

3.3 Effects of Gum Arabic and Calcium Chloride Coatings on Total Phenolic Content and Antioxidant Activity of Tarap Fruit

The total phenolic content and antioxidant activity of tarap fruit pulp in response to different coating treatments are presented in Table 2. Results indicated that both total phenolic content and FRAP activity were significantly affected by coating treatment and storage duration (P<0.01). However, no significant interaction effects were observed for DPPH and ABTS activities in the fruit pulp. Among all treatments, uncoated fruits exhibited a significantly higher total phenolic content (260.16 GAE/100 g fresh weight) compared to the coated samples. In contrast, fruits treated with a combination of 3% $CaCl_2$ and 5% GA recorded the lowest FRAP activity with 1,531,296 μmol TE/100 g fresh weight. This suggests that although this coating treatment might effectively preserved firmness and delayed ripening, it might also reduce antioxidant activity in fruits, potentially due to limited oxygen and light penetration which can restrict the biosynthesis of secondary metabolites. Similar observations were reported by [68], who found that a chitosan coating at various concentrations reduced total phenolic content in sweet cherries. This effect was attributed to the creation of modified atmosphere with reduced O_2 and elevated CO_2 levels which can inhibit the accumulation of secondary metabolites such as anthocyanins and phenolic compounds. In the present study, however, all coating treatments had no significant effect on DPPH and ABTS radical scavenging activities in the fruit pulp during 3 weeks of low temperature storage.

Table 2. Main and interaction effects of different coating treatments and storage weeks on DPPH and ABTS radical-scavenging activity, total phenolic content and ferric reducing antioxidant power of tarap fruit stored under cold storage at 10°C and 85-90% relative humidity.

Factors	DPPH inhibition (%)	ABTS inhibition (%)	TPC (mg GAE/100g FW)	FRAP (μmol TE/100 g FW)
Coating treatments (CT)				
Uncoated	5.88 a[z]	7.75 a	260.16 a	3,046,583 a
3% calcium chloride ($CaCl_2$)	5.56 a	7.27 a	91.61 b	2,611,163 a
5% gum arabic	6.39 a	14.14 a	128.71 b	2,799,688 a
3% $CaCl_2$ + 5% gum arabic	3.80 a	12.38 a	139.02 b	1,531,296 b
Storage week (SW)				
0	6.13 a	6.26 a	143.04 a	2,425,432 a
1	4.97 a	11.20 a	136.60 a	2,799,966 a
2	6.98 a	15.15 a	176.89 a	2,755,366 a
3	3.55 a	8.92 a	162.98 a	2,007,966 a
Interactions				
CT x SW	ns	ns	*	*

[z] Means followed by the same letter in the same column within factors are not significantly different at P≤0.05 according to Duncan's multiple range test.

*, ns Significant difference at P≤0.05 and not significant difference at P>0.05.

DPPH = 1,1-diphenyl-2-picryl hydrazyl, ABTS = 2-2'-azinobis-3-ethylbenzothiozoline-6-sulfonic acid, TPC = total phenolic content, FRAP = Ferric reducing antioxidant power, GAE = Gallic acid equivalent, TE = Trolox equivalent, FW = fresh weight

A distinct trend was observed in the uncoated tarap fruit whereby TPC was initially increased significantly and peaked at w 1 with 422.83 GAE/100 g fresh weight (FW), followed by a sharp decline to the lowest level by w 3 with 44.61 GAE/100 g FW (Figure 10). In other study on cold storage of Cogshall mangoes, phenolic compound levels in peel and pulp were initially increased which indicating the stress response to low temperature and thereafter declined during later ripening due to enzymatic oxidation in senescent tissue [69]. The transient rise in total phenolics was also attributed to induced phenylalanine ammonia lyase activity as defense response [70]. Conversely, all coated fruits exhibited delayed increase in TPC. This suggests that both coating treatments were effective in preserving phenolic compounds over time. Similarly, in Ponkan mandarins, it was observed that gum arabic (GA) coatings were able to retain higher total phenols and ascorbic acid during extended cold storage [20]. [21] reported that the GA which incorporated with African boabab extract resulted in gradual increases in total phenols and total anthocyanins as compared to the control blueberries during prolonged refrigerated storage. These finding suggests that both $CaCl_2$

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and GA coatings were able to preserve phenolic content in tarap fruit pulp by limiting free radical formation during 3 weeks of storage duration under low temperature.

The ferric reducing antioxidant power (FRAP) of tarap fruit pulp exhibited dynamic changes over the storage period across different coating treatments (Figure 11). The uncoated tarap fruit pulp maintained relatively stable FRAP value throughout storage. In contrast, fruit treated with 5% GA exhibited an increase in FRAP activity and peaked at w 2 before declining by w 3. Meanwhile, fruits treated with 3% $CaCl_2$ alone or in combination with GA maintained consistently lower FRAP values throughout the storage period. The lower FRAP values observed in the combined $CaCl_2$-GA treatment, despite superior firmness retention, can be explained by the formation of a semi-permeable coating matrix that reduces oxygen availability around the fruit surface. This leads to a slower respiration rate and delayed ripening processes, which in turn can influence metabolic pathways involved in the synthesis and accumulation of phenolic antioxidants that contribute to ferric reducing antioxidant capacity [12]. A related study on GA-zinc oxide nanoparticle composite coatings in Kinnow mandarins reported that coated fruits maintained significantly higher FRAP activity during storage compared to uncoated controls [71]. Edible coatings have been shown to reduce damage caused by reactive oxygen species and enhance antioxidant capacity in fruits thereby reducing physiological disorders and decay [72].

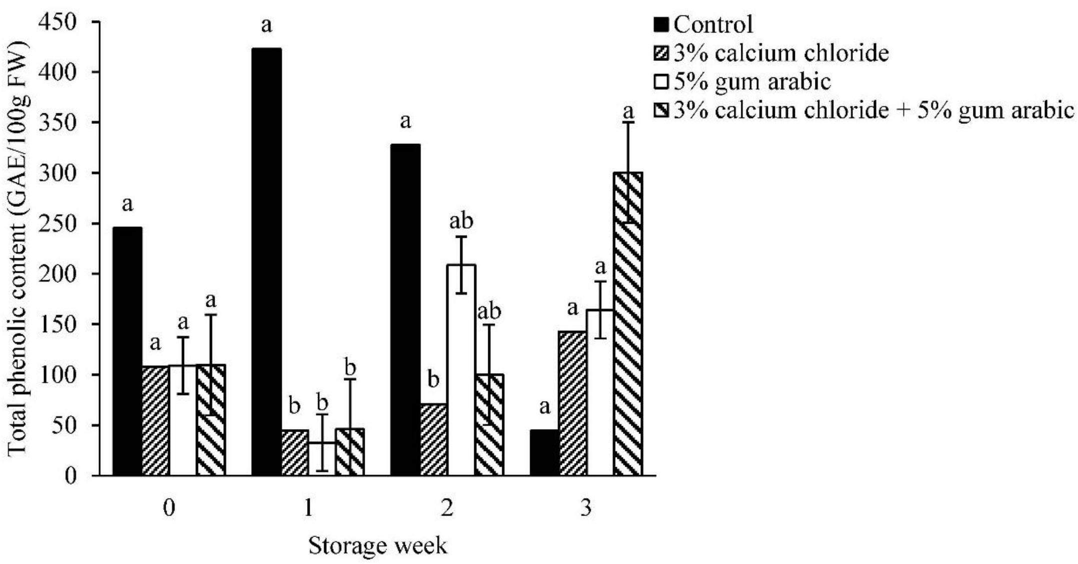

Figure 10. Effect of different coating treatments on total phenolic content of tarap fruit stored at 10°C and 85-90% relative humidity for 3 storage weeks. Different letters in each treatment are significantly different at P≤0.05 according to Duncan's multiple range test.

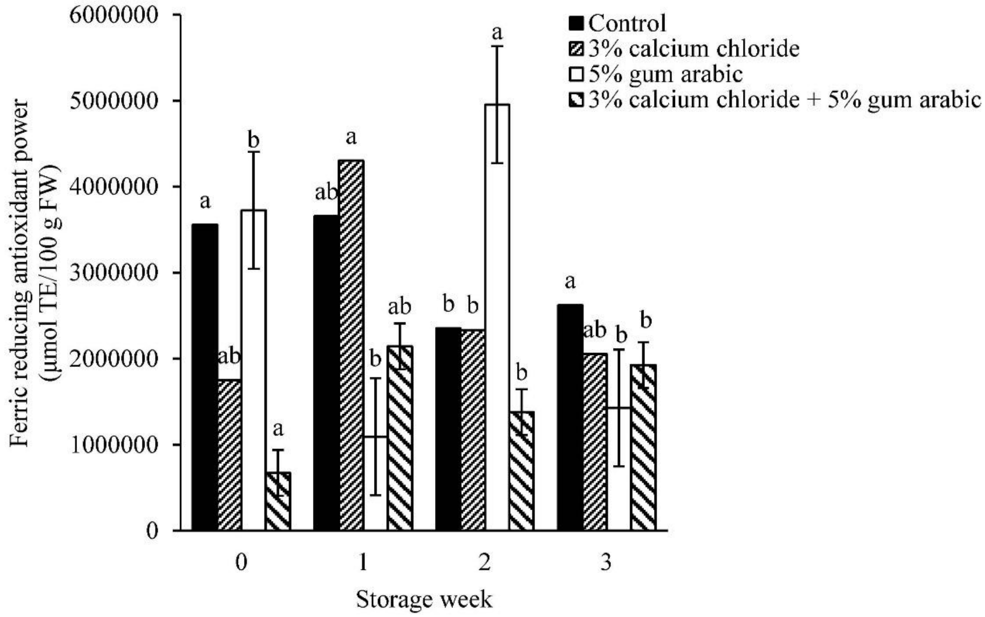

Figure 11. Effect of different coating treatments on FRAP activity of tarap fruit stored at 10°C and 85-90% relative humidity for 3 storage weeks. Different letters in each treatment are significantly different at P≤0.05 according to Duncan's multiple range test.

4. CONCLUSIONS

The application of gum arabic (GA) and calcium chloride ($CaCl_2$) coatings both individually and in combination significantly improved the physical and chemical quality of cold-stored tarap fruit. Among the treatments evaluated, the combined application of 3% $CaCl_2$ and 5% GA was most effective in preserving visual quality, maintaining peel and pulp firmness and delaying senescence, thereby extending the shelf life of the fruit from 1 week (uncoated) to 3 weeks. The treatment with 3% $CaCl_2$ alone best preserved texture and ascorbic acid content whereas 5% GA alone enhanced internal color and antioxidant properties of tarap fruit. The synergistic combination of $CaCl_2$ and GA provided the most comprehensive protection against postharvest deterioration. This formulation utilises generally recognised as safe (GRAS) materials and can be applied using postharvest techniques such as dipping or spraying during handling and packing. However, while the results are promising, the present study did not include formal sensory evaluation or detailed assessment of microbial spoilage and the storage conditions represented a controlled environment. Future studies should therefore incorporate sensory analysis, microbial assessments and dynamic storage conditions that better reflect real-world supply chains, as well as economic evaluations to further validate the commercial applicability of the $CaCl_2$-GA coating system for extending the shelf life and marketability of highly perishable tropical fruits such as tarap.

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AUTHOR CONTRIBUTIONS

Nuratika Tamimi Sheikh Mohamed: Conceptualization, Methodology, Supervision, Project administration, Funding acquisition. **Clayrieysa Samantha Michael Solomon:** Data curation, Investigation, Writing - Original draft preparation. **Shiamala Devi Ramaiya:** Methodology, Formal analysis, Validation, Writing - Review and Editing. **Hanisah Kamilah:** Methodology, Validation, Resources, Writing - Review and Editing. **Noorasmah Saupi:** Resources, Funding acquisition. **Khairunnasrin Binti Hamzah: Writing -** Review and Editing.

CONFLICT OF INTEREST STATEMENT

The authors declare that they hold no competing interests.

DECLARATION OF GENERATIVE AI IN PREPARATION OF MANUSCRIPT

During the preparation of this work, the authors used ChatGPT to improve the readability and language of the manuscript. After using this tool, the authors reviewed and edited the content as necessary and took full responsibility for the publication's content.

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