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Effect of Gum Arabic and Starch-Based Coating and Different Polyliners on Postharvest Quality Attributes of Whole Pomegranate Fruit

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Abstract: This study investigated the effect of gum Arabic and starch-based coating and two polyliners (Liner 1-micro-perforated Xtend® and Liner 2-macro-perforated high-density polyethylene) on whole 'Wonderful' pomegranate fruit during cold storage (5 ± 1 °C and 95 ± 2% RH). Uncoated (UC) and coated (GA_{MS}) fruit were packaged into standard open top ventilated cartons (dimensions: 0.40 m long, 0.30 m wide and 0.12 m high) with (GA_{MS} + Liner 1, GA_{MS} + Liner 2, UC + Liner 1 and UC + Liner 2) or without (UC and GA_{MS}) polyliners. After 42 d, treatment GA_{MS} + Liner 1 recorded the least weight loss (4.82%), whilst GA_{MS} recorded lower (8.77%) weight loss than UC + Liner 2 (10.07%). The highest (24.74 $mLCO_2\ kg^{-1}h^{-1}$) and lowest (13.14 $mLCO_2\ kg^{-1}h^{-1}$) respiration rates were detected in UC and GA_{MS} + Liner 1, respectively. The highest and lowest total soluble solids were recorded for GA_{MS} (16.87 °Brix), and GA_{MS} + Liner 1 (15.60 °Brix) and UC + Liner 1 (15.60 °Brix), respectively. Overall, no decay was detected for coated fruit packaged with either Liner 1 or Liner 2. Therefore, the combination of GA_{MS} with Xtend® polyliners proved to be an effective treatment to maintain the quality of 'Wonderful' pomegranates during storage.

Keywords: polyliner; packaging; postharvest technology; pomegranate fruit; quality; edible coating

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1. Introduction

Pomegranate (*Punica granatum* L.) is a highly nutritional fruit classified botanically as a berry and belonging to the Lythraceae family [1–3]. Originally native of Iran and bearing a Persian name 'Anar', it is now extensively grown worldwide in tropical and subtropical regions for local consumption and export [2,4]. The seeds/arils are the edible portions of the fruit bearing remarkable sensory properties and a considerable number of bioactive compounds, including polyphenols, polysaccharides, sugars and vitamins [5,6]. In epidemiological research, these phytochemicals and antioxidants have been found to exhibit protective role in human health against diseases [7,8]. Furthermore, scientific reports indicate the potent anti-mutagenic, anti-hypertension and anti-inflammatory properties associated with the therapeutic compounds of pomegranate juice and products [9–11]. The evidence from studies investigating the health benefits of pomegranate juice consumption has contributed significantly to the global increase in consumer preference and production of the fruit [10,11].

Pomegranate is classified as a non-climacteric fruit; however, it is regarded as a perishable commodity despite being characterized by low respiration rates after harvest [1–3]. Elyatem and Kader [12] observed 'Wonderful' pomegranate stored between 0–10 °C recorded respiration rate of less than 8 $mLCO_2\ kg^{-1}h^{-1}$ during a storage period of 3 months. Similarly, Mphahlele et al. [13] reported that 'Wonderful' pomegranates stored in different packaging materials at 7 ± 0.5 °C and 90 ± 5% relative humidity (RH) for 4 months exhibited respiration rates below 6 $mLCO_2\ kg^{-1}h^{-1}$. However, the fruit is susceptible to physiological disorders such as chilling injury and scald when stored at low temperatures (−1–10 °C) [12]. Mirdehghan et al. [14] showed that untreated 'Mollar de Elche' pomegranate developed over 44% skin browning and 58% electrolyte leakage as symptoms of chilling injury during 90 d of storage at 2 °C followed 3 d at 20 °C. The loss of total organic acid content [15,16] and total soluble solids [17] has been highlighted in pomegranate cultivars such as 'Bhagwa', 'Ruby' and "Hicaznar' during storage at different storage conditions (5–10 °C and 90–92% RH) for up to 6 months. In addition, a high risk of decay development has been reported during cold storage and shelf life. For instance, Çandir et al. [18] observed 37% decay incidence in 'Hicaznar' pomegranate after 6 months of cold storage (6 ± 0.5 °C and 90 ± 5% RH) and subsequent shelf-life period (20 ± 1 °C and 70 ± 5% RH). These physiological and pathological disorders result in postharvest losses, which can rise to 30% in some cultivars, significantly reducing profitability and growth of the pomegranate fruit industry [19]. Therefore, maintenance of postharvest quality and microbial safety of the fruit is a major challenge to sustain the availability of the fruit on the consumer market [19,20]. Extensive scientific studies have been done to alleviate postharvest losses, including the application of both physical and chemical treatments [19]. Postharvest technologies applied to preserve quality include controlled atmosphere, organic acids, heat treatments, fungicides, irradiation and modified atmospheric packaging [19]. Despite these notable research efforts, significant quality losses are still being observed during postharvest handling, storage and export of the fruit [19,20].

During postharvest handling, storage and export, pomegranate fruit is usually packaged in a multi-layered system which consists of components such as cardboard ventilated carton, polyliners and a carry bag [21–23]. This multi-layered packaging system is a postharvest tool that preserves the quality of fresh whole pomegranate fruit [23]. Polyliners, described as passive modified atmosphere packaging (MAP), are an important part of the system with distinct permeability to gases, water vapor and different perforations [23–25]. To extend fruit storage and shelf life, polyliners are designed to minimize weight loss, respiration rate, condensation of water vapor and microbial proliferation [23,24,26]. For instance, studies by Lufu et al. [21] recommended the use of micro-perforated Xtend® and macro-perforated (2 mm) polyliners to reduce weight loss and the development of decay in 'Wonderful' pomegranates during cold storage (5 °C). Similarly, Selcuk and Erkan [27] found that 'Hicrannar' pomegranates packaged in Xtend® and ZOEpac® polyliners, recorded the least weight loss and decay development during a 120 d cold storage (6 °C). Moreover, the successful application of plastic packaging in pomegranate fruit has been reported for several cultivars which include 'Ganesh' and 'Primosole' [28,29]. In general, polyliners and other forms of plastic packaging exhibit good mechanical performance such as tensile and tear strength, good barrier to gases and aroma compounds [23,30,31]. However, with consumer trends showing a preference for no-plastic and eco-friendly packaging, the use of polyliners is no longer considered as a not environmentally friendly postharvest tool for quality maintenance in pomegranate fruit [32]. Furthermore, there are high costs associated with using plastic polyliners when packaging fruit using the multi-layered packaging system. Moreover, with plastic production superseding recycling and waste disposal being a pressing environmental concern leading to air and water pollution, there is an urgent need for alternative postharvest technologies [33,34].

Several biodegradable postharvest technologies have been suggested to alleviate the postharvest losses in fresh produce [35–37]. However, studies have suggested that the complete replacement of plastic packaging with eco-friendly packaging films may be impossible for certain food types [31]. Furthermore, limited studies have proven the efficacy of biodegradable alternatives to deliver improved packaging outcomes for several fresh produce, including the pomegranate fruit. Nevertheless, in recent times, the use of biodegradable and edible coatings has shown great potential as an alternative postharvest technology in fresh fruit to preserve quality and extend storage life [38–40].

Edible coatings are usually applied directly on the surface of fresh fruit in spraying form and allowed to dry, forming additional protection against moisture loss and microbial proliferation [41]. Depending on the physiology of specific fresh fruit and the storage conditions, different edible coatings can be applied, including polysaccharides and their derivatives, proteins, fats and combination or composites [42–44]. Several studies have demonstrated the efficacy of edible coatings to minimize weight loss and decay incidence in different pomegranate cultivars during cold storage [45–49]. Similar results have also been reported for edible coating applications in fruit types, such as citrus [50], avocado [51], melon [52], passion fruit [53] and pineapple [54]. However, the application is still limited because some coatings inhibit respiratory gas exchange in fresh produce, resulting in fermentation, ethanol accumulation and a bitter taste [55,56]. Moreover, the emission of certain volatiles under such conditions may lead to off-flavors and reduction of sensory quality [57].

In most studies, edible coatings are combined with other technologies such as MAP and organic acids to reduce weight loss, decay incidence and improve quality characteristics of fresh produce [47]. For instance, De Reuck et al. [58] found that application of chitosan coating and biorientated polypropylene packages on 'Mauritius' and 'McLean's Red' litchi, resulted in the best overall fruit quality compared to uncoated control or biorientated polypropylene packages alone. Recently, Kawhena et al. [49] showed that gum Arabic and maize starch-based coatings reduced weight loss in 'Wonderful' pomegranate packaged in Xtend® polyliners during 42 d of cold storage (5 ± 1 °C) and 5 d at ambient temperature (20 ± 0.2 °C). Beyond similar research, there is limited information on the effect of edible coatings without plastic packaging on the quality attributes of pomegranate fruit during cold storage. To our best knowledge, there are no studies available exploring the possibility of replacing polyliners with edible coatings as a biodegradable alternative in the packaging of pomegranate fruit. The present study was designed to evaluate the effect of different composite edible coatings on postharvest storage and shelf life of 'Wonderful' pomegranate fruit as potential substitutes for selected polyliners commonly used in pomegranate fruit industry.

2. Materials and Methods

2.1. Fruit Procurement

Fresh 'Wonderful' pomegranate fruit harvested at commercial maturity were purchased from Sonlia Pack-house (33°34′851″ S, 19°00′360″ E) in Western Cape, South Africa. Fruit were sanitized by immersion in milli–Q water, ethanol solution (700 $g \cdot L^{-1}$) and sodium hypochlorite (3.5 $g \cdot L^{-1}$) following the procedure reported by Munhuweyi et al. [59]. Subsequently, fruit were briefly stored (5 ± 1 °C, 95 ± 2% RH) before applying coating solutions.

2.2. Formulation of Coating Solutions

The coating solutions consisting of gum Arabic (0.5% *w*/*v*) (Sigma-Aldrich, Johannesburg, South Africa), maize starch (0.5% *w*/*v*) (Chem. lab suppliers Co., Johannesburg, South Africa), glycerol (1% *v*/*v*) (Sigma-Aldrich, Johannesburg, South Africa), tween 80 (0.05% *v*/*v*) (Sigma-Aldrich, Johannesburg, South Africa) and lemongrass oil (3% *v*/*v*) (Umuthi Botanicals, Wilderness, South Africa) were prepared in 1000 mL mill-Q water according to optimization procedure conducted by Kawhena et al. [49]. The solutions were continuously stirred at low heat (25 °C) for 1 h on a hot plate magnetic stirrer (Spinot, Tarsons, New Delhi, India). Subsequently, the coating solutions were filtered through a cheese cloth, and homogenized at 2500 r.p.m. for 30 min in an overhead stirrer (Scientech Co., Indore, India).

2.3. Packaging and Storage

A completely randomized design was applied to arrange all treatment combinations (coating × polyliner). The sanitized whole pomegranate fruit were coated by dipping for 1 min in the prepared coating solution (GA_{MS}). The coated pomegranates were allowed to dry for 30 min at 20 ± 0.2 °C and 60 ± 10% RH and hand-packaged with either micro (20 µm) perforated Xtend® (StePac Co., Antalya, Turkey) plastic liner (Liner 1) or macro (4 mm) perforated high density polyethylene liner (Line 2) (Figure 1). Thereafter, fruit were packaged into standard open top ventilated cartons (dimensions: 0.40 m long, 0.30 m wide and 0.12 m high) (10 fruit per carton). Fruit that were coated and packaged into ventilated cartons without polyliners were included as a treatment in the experiment. Furthermore, uncoated fruit packaged without polyliners in standard open top ventilated cartons served as the control. Fruit were stored (5 ± 1 °C, 95 ± 2% RH) for 42 d and postharvest evaluations were done at every 7-day interval and after 5 d at ambient temperature (20 ± 0.2 °C and 60 ± 10% RH). All treatment combinations are summarized in Table 1.

(**a**) (**b**) (**c**)

Figure 1. Pomegranate fruit (cv Wonderful) packaging treatments (**a**) without a polyliner in standard open top ventilated cartons, (**b**) with a microperforated Xtend® liner (20 µmm perforation) in standard open top ventilated cartons and (**c**) with a macroperforated high density polyethylene liner (4 mm perforation) in standard open top ventilated cartons.

Table 1. Summary of treatment combinations applied on 'Wonderful' pomegranate before cold storage (5 ± 1 °C, 95 ± 2% RH) and shelf life (20 ± 0.2 °C and 60 ± 10% RH).

Treatment	Description
GA_{MS} + Line 1	Pomegranate fruit coated with GA_{MS}, packaged with Liner 1 (micro-perforated Xtend® liner, 20 µmm perforation) in standard open top ventilated cartons
GA_{MS} + Line 2	Pomegranate fruit coated with GA_{MS}, packaged in Liner 2 (macro-perforated high density polyethylene liner, 4 mm perforation) in standard open top ventilated cartons
UC + Line 1	Uncoated fruit packaged with Liner 1 (micro-perforated Xtend® liner, 20 µmm perforation) in standard open top ventilated cartons
UC + Line 2	Uncoated fruit packaged with Liner 2 (macro-perforated high density polyethylene liner, 4 mm perforation) in standard open top ventilated cartons
GA_{MS}	Pomegranate fruit coated with GA_{MS}, packaged without polyliner in standard open top ventilated cartons
UC	Uncoated fruit packaged without polyliner in standard open top ventilated cartons

2.4. Physiological Response

2.4.1. Weight Loss

Weight loss was determined according to Kawhena et al. [49] using an electronic weighing balance (ML3002.E, Mettler Toledo, Zurich, Switzerland). For each treatment combination, the weight of ten randomly selected fruit was continuously measured during storage, and weight loss was calculated using the following Equation (1):

$$W_L = (W_O - W_t)/W_O \times 100 \quad (1)$$

where W_L is weight loss (%), W_O is the initial weight (g) of fruit and Wt is the fruit weight (g) at the time of analysis.

2.4.2. Respiration Rate

The method reported by Caleb et al. [60] was adopted to determine respiration rate from CO_2 evolution of pomegranate fruit measured in a closed system using a gas analyzer (Checkmate 3, PBI Dansensor, Ringstead, Denmark). Before all measurements, the gas analyzer was auto calibrated with the atmospheric gas composition. Briefly, in triplicates for each treatment combination, three fruit were stored (20 ± 0.2 °C and 60 ± 10% RH) for 2 h in a sealed glass jar (volume = 3 L) with a lid containing a rubber septum in the middle. The CO_2 produced was determined from the headspace through the rubber septum and the results were expressed as a percentage of CO_2 gas.

2.5. Physiological and Pathological Disorders

2.5.1. Shriveling

The incidence of shriveling was visually assessed in triplicate of 15 randomly selected fruit per treatment after 7-day interval and after 5 d at ambient temperature (20 ± 0.2 °C and 60 ± 10% RH) following the procedure reported by Palou et al. [61]. Shriveling was expressed as a percentage of the total fruit assessed.

2.5.2. Decay Incidence and Fruit Internal Decay

The visual assessment of external decay was done in triplicates of 15 randomly selected fruit per treatment combination at every 7-day interval and after 5 d at ambient temperature (20 ± 0.2 °C and 60 ± 10% RH) sampling period as described by Hussein et al. [62]. To measure external decay, the surface of the fruit was examined for mycelia development. The visible decay was expressed as a percentage of the total fruit assessed using Equation (2):

$$\text{Decay incidence} = (\text{Number of decayed fruit}/\text{Total number of fruit assessed}) \times 100\% \quad (2)$$

Subsequently, internal decay was determined by cutting fruit along the equatorial axis and carefully inspecting arils, and visible decay was expressed as a percentage of the total fruit assessed using Equation (3):

$$\text{Internal decay} = (\text{Number of fruit with decayed arils}/\text{Total number of fruit assessed}) \times 100\% \quad (3)$$

2.6. Physicochemical Properties

2.6.1. Color

The color of fruit surface was determined in CIELAB coordinates (L*, a*, b*) using a pre-calibrated Minolta Chroma Meter CR-400 (Minolta Corp., Osaka, Japan) [62]. The instrument was calibrated using a standard white tile, Illuminate D 65, and a 10° standard observer. For each treatment combination, color was measured from ten randomly selected fruit along the equatorial axis of each fruit at two opposite spots. The chroma (C*) and hue angle (h°) were calculated from Equations (4) and (5),

$$\text{Chroma } (C^*) = (a^{*2} + b^{*2})^{1/2}) \quad (4)$$

$$\text{Hue angle } (h^\circ) = \arctan (b^*/a^*) \quad (5)$$

2.6.2. Total Soluble Solids and Titratable Acidity

Using a blender (Mellerware, Cape Town, South Africa), homogenized pomegranate juice (PJ) was obtained from arils extracted from ten randomly selected fruit per treatment combination. In triplicates, total soluble solids (TSS) were determined at each interval using a digital refractometer (Atago, Tokyo, Japan), and results were expresses as degree Brix (°Brix) [62]. A titration method was used to measure titratable acidity (TA) of PJ per treatment combination. Briefly, in triplicates, 2 mL of PJ was mixed with 70 mL of milli-Q water and titrated against NaOH (0.1 N) to an endpoint of pH = 8.2 using a Metrohm 862 compact titrosampler (Herisau, Switzerland). The TA was expressed as a percentage of citric acid equivalents (% CA) [62].

2.7. Total Phenolic Content and Free Radical Scavenging Activity

2.7.1. Total Phenolic Content

A microplate technique reported by Horszwald and Andlauer [63] was adopted to determine the total phenolic content (TPC) of PJ using the Folin–Ciocalteu method. Briefly, 100 µL of Folin-C (10 %) solution were added to 20 µL of six-fold diluted PJ in a 96-well microplate reader and incubated for 3 min at room temperature. After the incubation period, 80 µL of sodium carbonate (7.5% *w*/*v*) were added, and the solution was heated for 1 h at 30 °C in an oven (Model nr. 072160, Prolab Instruments, Sep Sci., Johannesburg, South Africa). The absorbance of the solution was determined spectrophotometrically at 750 nm and results were expressed in mL gallic acid equivalent (GAE) per liter mg GAE/LPJ.

2.7.2. Free Radical Scavenging Activity

Free radical scavenging activity (RSA) of PJ was measured spectrophotometrically according to the procedure described by Horszwald and Andlauer [63] incorporating slight modifications. A volume of 200 µL of 1,1-diphenyl-2-picryl-hydrazyl (DPPH) working solution was added to 100 µL of 6-fold diluted sample. Following an incubation period (5 min) at room temperature, the absorbance of samples, standards and blanks were determined spectrophotometrically at 520 nm using a 96-well microplate reader. Equation (6) was applied to calculate the final test absorbency:

$$\text{Test absorbency} = \text{blank absorbency} - (\text{test absorbency} - \text{color correction absorbency}) \quad (6)$$

The results for RSA of PJ were expressed as ascorbic acid (millimoles) equivalent per litre of pomegranate juice (mM AAE/LPJ).

2.8. Statistical Analysis

All experimental data were analyzed using analysis of variance (ANOVA) using SAS Software (SAS Enterprise Guideline 7.1, Carey, NC, USA). Least significant differences (LSD) were calculated according to Duncan's Multiple Range test to separate differences ($p < 0.05$). Graphical presentations were made using GraphPad Prism software version 8.4.3 (GraphPad Software, Inc., San Diego, CA, USA).

3. Results

3.1. Physiological Response

3.1.1. Weight Loss

There was an increase in the weight loss of 'Wonderful' pomegranates during storage in all treatments (Figure 2). However, the loss was significantly ($p < 0.0001$) lower in coated fruit packaged with or without polyliners (GA_{MS}, GA_{MS} + Liner 1 and GA_{MS} + Liner 2) than in uncoated fruit packaged without polyliner (UC). Interestingly, from day 7 to day 42, fruit coated with GA_{MS} and packaged without polyliners (GA_{MS}) recorded lower (8.77%) weight loss than uncoated fruit packaged with Liner 2 (UC + Liner 2 = 10.07%). After 42 days of storage, the order of magnitude of weight loss in treatments was UC (12.65%) >

UC + Liner 2 (10.07%) > GA_{MS} (8.77%) > UC + Liner 1 (6.95%) > GA_{MS} + Liner 2 (5.54%) > GA_{MS} + Liner 1 (4.82%).

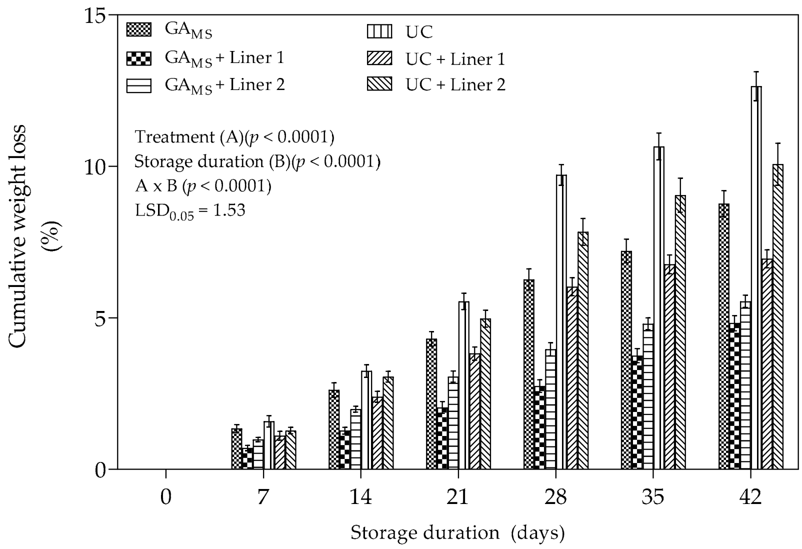

Figure 2. Cumulative weight loss (%) of 'Wonderful' pomegranate coated and packaged in different polyliners and stored (5 ± 1 °C, 95 ± 2% RH) for 42 d. GA_{MS}—gum Arabic (0.5% *w*/*v*) and maize starch (0.5% *w*/*v*); Liner 1—Xtend® liner (20 µmm perforations); Liner 2—perforated liner (4 mm perforations); UC—uncoated fruit. $LSD_{0.05}$ represents least significant difference ($p < 0.05$).

3.1.2. Respiration Rate

The coating treatments significantly ($p < 0.0001$) affected the respiration rate of 'Wonderful' pomegranates during storage and shelf life (Figure 3). From day 0 to day 21, a gradual increase in respiration rate was observed for all treatments. However, the rate of increase was significantly lower in coated fruit packaged with or without polyliners (GA_{MS}, GA_{MS} + Liner 1 and GA_{MS} + Liner 2) than in uncoated fruit without packaging (UC). In the same period, GA_{MS} recorded a lower respiration rate than UC + Liner 2 (day 7), and there was no significant difference between the treatments from day 7 to day 35. Overall, from day 21 to day 42, there was a decrease in respiration rate across all treatments. However, GA_{MS} + Liner 1, GA_{MS} + Liner 2 exhibited the lowest respiration rate compared to other treatments. Likewise, there was no significant difference in respiration rate between coated fruit without polyliner (GA_{MS}) and treatments UC + Liner 1 and UC + Liner 2. On day 42, the highest (24.74 mL CO_2 $kg^{-1}h^{-1}$) and lowest (13.14 mL CO_2 $kg^{-1}h^{-1}$) respiration rates were recorded in fruit subjected to uncoated fruit without packaging (UC) and GA_{MS} + Liner 1, respectively.

3.2. Physiological and Pathological Disorders

3.2.1. Shriveling

Visible symptoms of shriveling were observed on coated fruit packaged without a polyliner-GA_{MS} (8.33%) and uncoated fruit packaged without a polyliner-UC (13.33%) after 21 d of storage (Figure 4a). After 42 d, uncoated fruit without packaging (UC) and GA_{MS} recorded the highest (100%) and lowest (13.33%) shriveling incidence. For the entire storage duration, no symptoms of shriveling were observed for fruit subjected to all coated fruit packaged with the investigated liners.

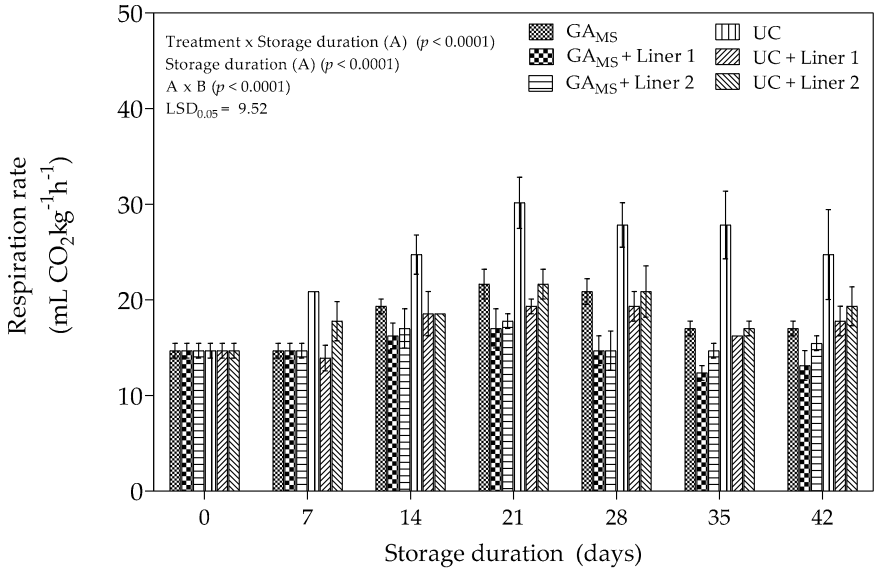

Figure 3. Respiration rate (mLCO_2 $kg^{-1}h^{-1}$) of 'Wonderful' pomegranate coated and packaged in different polyliners and stored (5 ± 1 °C, 95 ± 2% RH) for 42 d. GA_{MS}—gum Arabic (0.5% *w*/*v*) and maize starch (0.5% *w*/*v*); Liner 1—Xtend® liner (20 µmm perforations); Liner 2—perforated liner (4 mm perforations); UC—uncoated fruit. $LSD_{0.05}$ represents least significant difference ($p < 0.05$).

3.2.2. Decay Incidence and Internal Decay

The incidence of decay was observed after 14 d for uncoated fruit packaged without polyliners (UC) (3.33%) (Figure 4b). After 42 d, treatments UC, GA_{MS}, UC + Liner 1 and UC + Liner 2 recorded decay incidence of 50.00%, 13.33%, 1.67% and 1.67%, respectively. For the entire storage period, no decay was detected for all coated fruit packaged with either Liner 1 or Liner 2 (GA_{MS} + Liner 1, GA_{MS} + Liner 2). Similarly for internal decay was detected after 14 d for treatments GA_{MS} + Liner 1 (1.67%) and UC (1.67%) (Figure 4b). During the 42 d of storage, no internal decay was detected for treatments GA_{MS} + Liner 1, UC + Liner 1 and UC + Liner 2.

3.3. Physicochemical Properties

3.3.1. Color Attributes

The change in color attributes (L* and a*) as a function of storage time for coated and uncoated 'Wonderful' pomegranates is shown in Figure 5. For all treatments, there was an increasing trend in L* values between day 0 to day 28, with the pattern of change more pronounced for uncoated fruit without packaging (UC) (Figure 5a) from day 28 to day 42, L* values remained more or less constant, with a significant decrease observed for some treatments, including GA_{MS} + Liner 1 and UC + Liner 1. In general, coated fruit with or without packaging maintained L* values lower than uncoated fruit without packaging (UC). Moreover, for extended storage periods, treatments UC + Liner 1 and UC + Liner 2 recorded lower L* values than treatment UC.

Between day 0 and day 7, treatment UC recorded a* values more or less equal to other coated fruit with or without packaging (Figure 5b). However, between day 21 and day 35, fruit coated and packaged with/without packaging (GA_{MS} + Liner 1) mostly maintained higher positive values than uncoated fruit (UC). In particular, on days 14, 21 and 28, GA_{MS} + Liner 1 recorded the highest a* values than all treatments. Overall, from day 14 to day 42, there was a decrease in redness of fruit for most treatments. However, the decreasing pattern mainly was more pronounced for uncoated fruit without packaging (UC). Similarly, for C* values, between day 14 and day 35, coated fruit packaged with/without liners recorded higher values than uncoated fruit packaged without polyliners (UC) (Figure 6a). During this period, C* values mostly decreased for uncoated fruit without packaging (UC). In addition, between day 14 and 42, uncoated fruit packaged with liners (UC + Liner 1 and UC + Liner 2) exhibited higher values than uncoated fruit packaged without liners (UC). For h° values, between day 0 and day 28, treatment UC presented lower values than other treatments (Figure 6b). However, on day 28, UC recorded higher h° values than all treatments.

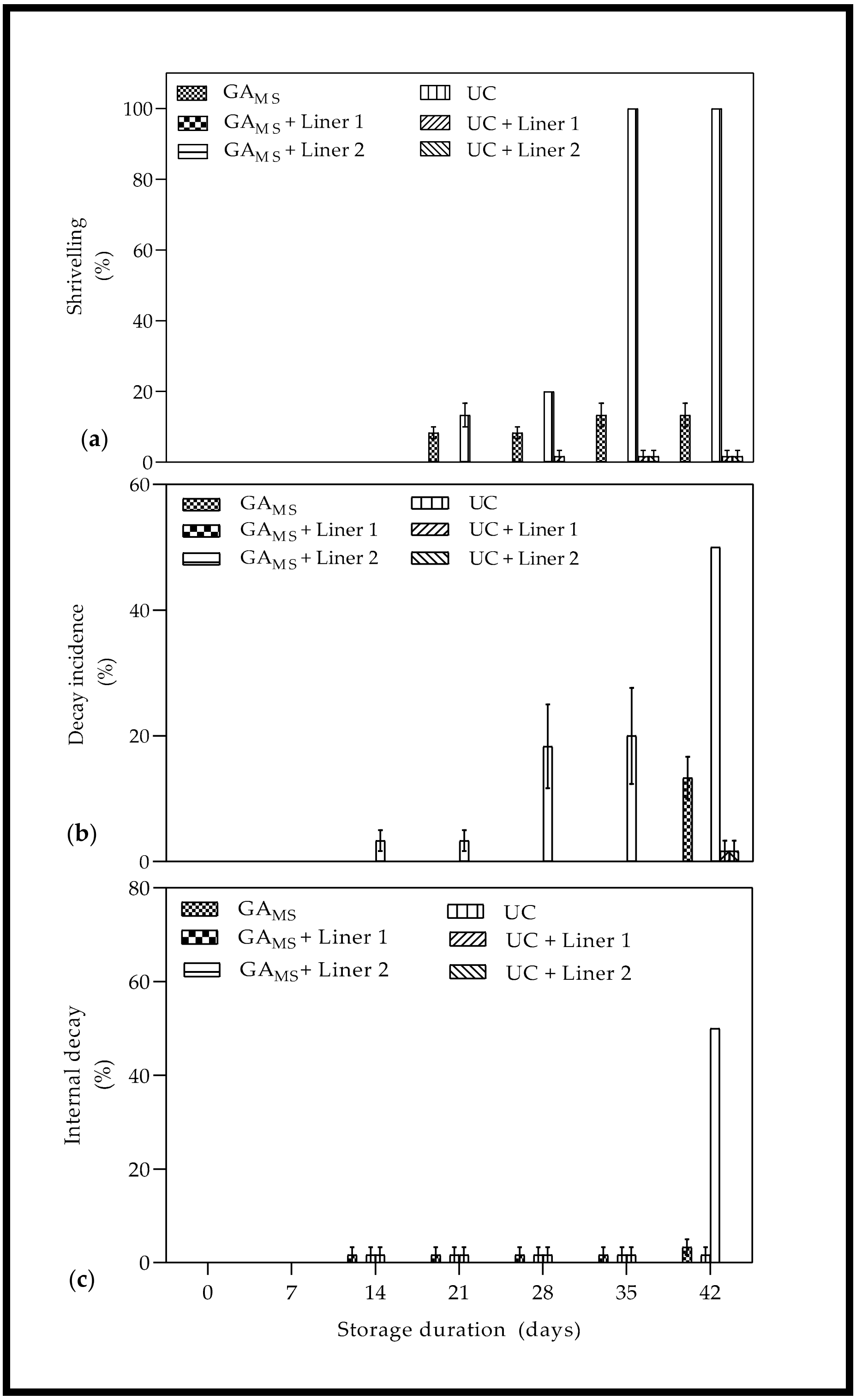

Figure 4. Incidence of (**a**) Shriveling, (**b**) external decay and (**c**) internal decay in 'Wonderful' pomegranate coated and packaged in different polyliners and stored (5 ± 1 °C, 95 ± 2% RH) for 42 d. GA$_{MS}$—gum Arabic (0.5% *w*/*v*) and maize starch (0.5% *w*/*v*); Liner 1—Xtend® liner (20 µmm perforations); Liner 2—perforated liner (4 mm perforations); UC—uncoated fruit.

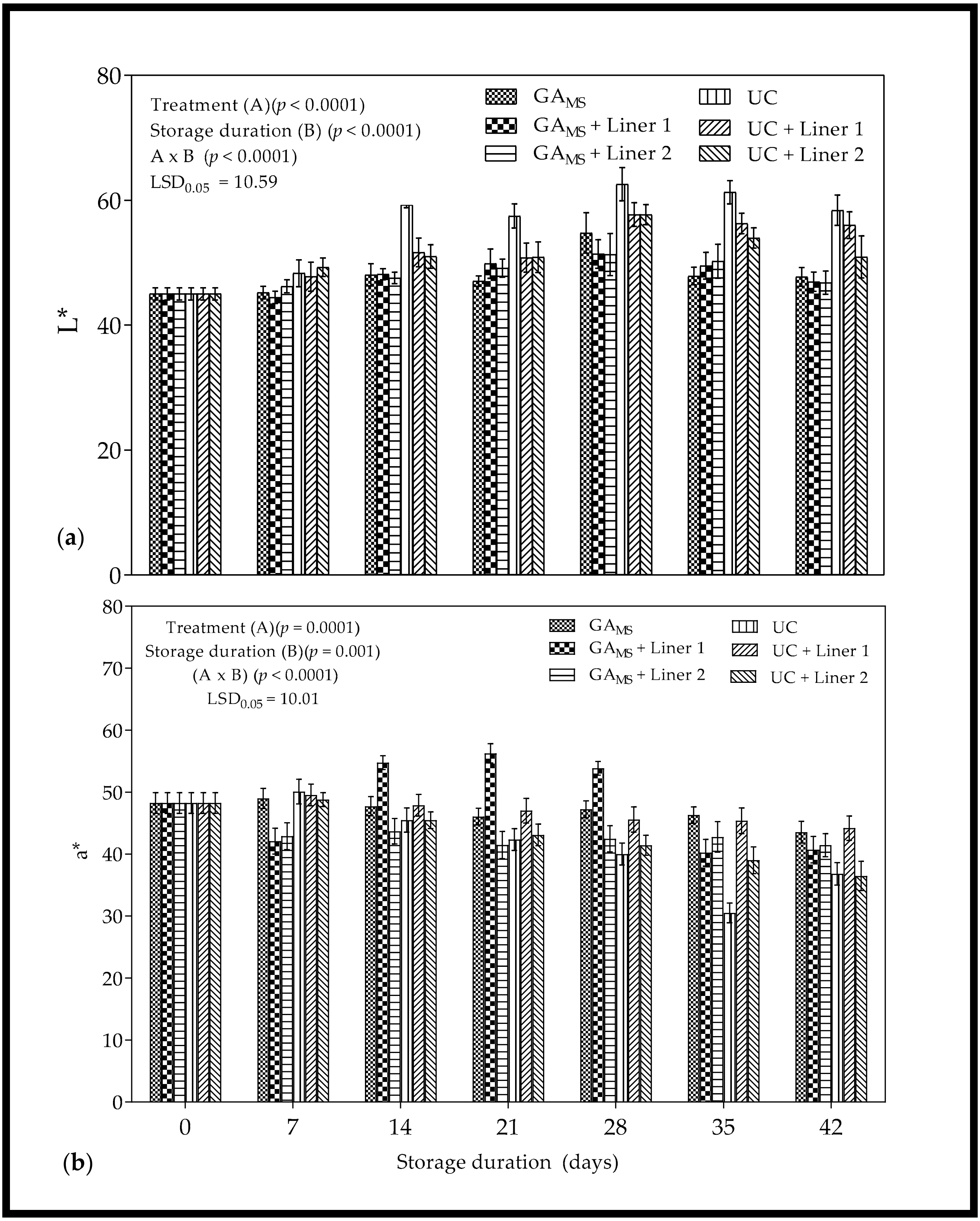

Figure 5. Color attributes (**a**) lightness (L*) and (**b**) redness/greenness (a*) of 'Wonderful' pomegranate coated and packaged in different polyliners and stored (5 ± 1 °C, 95 ± 2% RH) for 42 d. GA_{MS}—gum Arabic (0.5% *w*/*v*) and maize starch (0.5% *w*/*v*); Liner 1—Xtend® liner (20 µmm perforations); Liner 2—perforated liner (4 mm perforations); UC—uncoated fruit. $LSD_{0.05}$ represents least significant difference (p < 0.05).

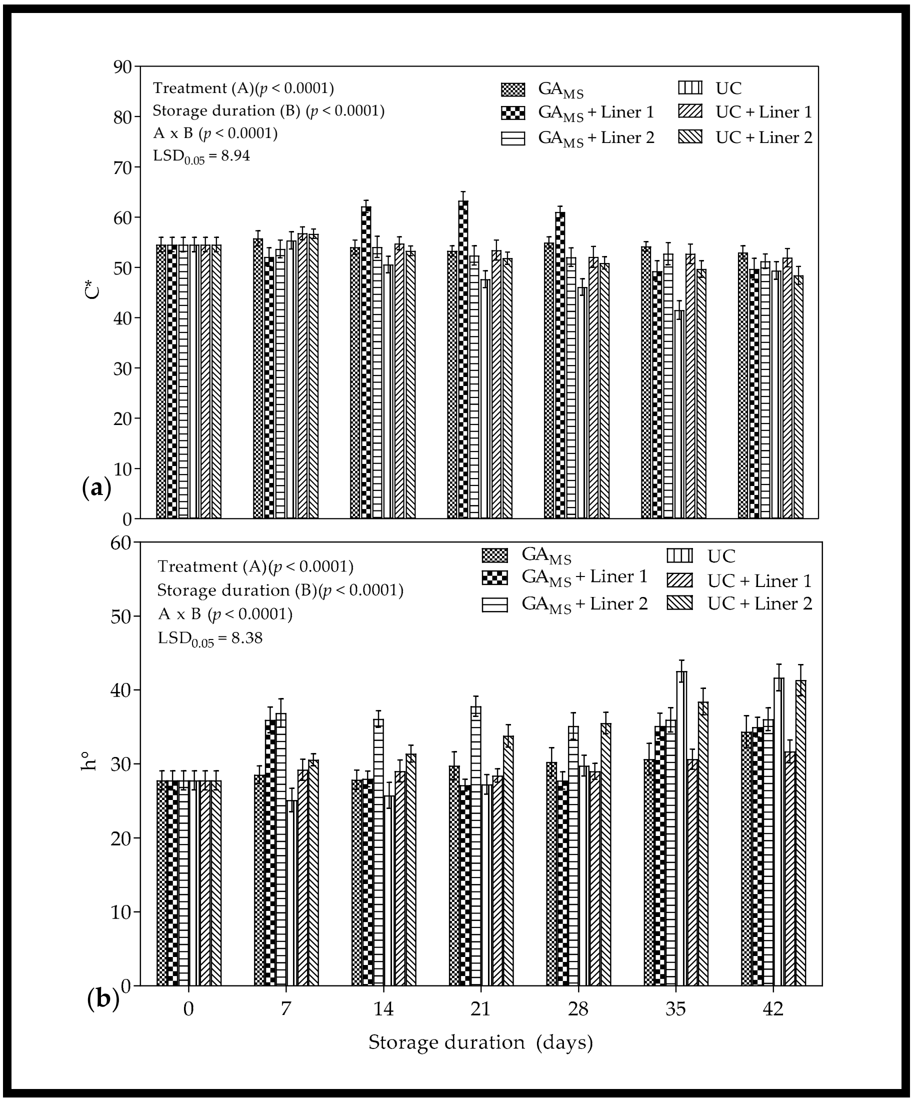

Figure 6. Color attributes (**a**) chroma (C*) and (**b**) hue angle (h°) of 'Wonderful' pomegranate coated and packaged in different polyliners and stored (5 ± 1 °C, 95 ± 2% RH) for 42 d. GA_{MS}—gum Arabic (0.5% *w*/*v*) and maize starch (0.5% *w*/*v*); Liner 1—Xtend® liner (20μmm perforations); Liner 2—perforated liner (4 mm perforations); UC—uncoated fruit. $LSD_{0.05}$ represents least significant difference ($p < 0.05$).

3.3.2. Total Soluble Solids and Titratable Acidity

The TSS content of aril juice showed an increasing trend during 42 d of cold storage from harvest (day 0) (Figure 7a). However, from day 7 to day 28, treatments GA_{MS} + Liner 1 and GA_{MS} + Liner 2 significantly delayed the increase in TSS compared to treatments UC, UC + Liner 1 and UC + Liner 2. Treatment GA_{MS} recorded lower TSS content than UC + Liner 2 on day 7 (GA_{MS} = 14.50 °Brix; UC + Liner 2 = 15.33 °Brix) and day 28 (GA_{MS} = 16.40 °Brix; UC + Liner 2 = 16.97 °Brix). After 42 days of storage, the highest and lowest TSS content were recorded for treatments GA_{MS} (16.87 °Brix), and GA_{MS} + Liner 1 (15.60 °Brix) and UC + Liner 1 (15.60 °Brix), respectively. For TA, a progressive decrease was observed for uncoated fruit (UC) during 42 d of storage (Figure 7b). In contrast, the decrease in TA was retarded in fruit coated and packaged with polyliners (GA_{MS} + Liner 1 and GA_{MS} + Liner 2). Furthermore, between day 7 and day 28, GA_{MS} maintained TA levels higher than uncoated fruit (UC). After 42 d of storage, the highest (1.21% CA) and lowest (0.99% CA) TA content was recorded for GA_{MS} + Liner 1 and UC treatments, respectively. Figure 7c shows the change in TSS/TA as a function of storage duration for

'Wonderful' pomegranates. Generally, there was an increase in TSS/TA in all treatments during 42 d of storage. However, the rate of increase was significantly lower for coated fruit packaged with polyliners. Treatment GA_{MS} maintained TSS/TA levels lower than uncoated fruit (UC).

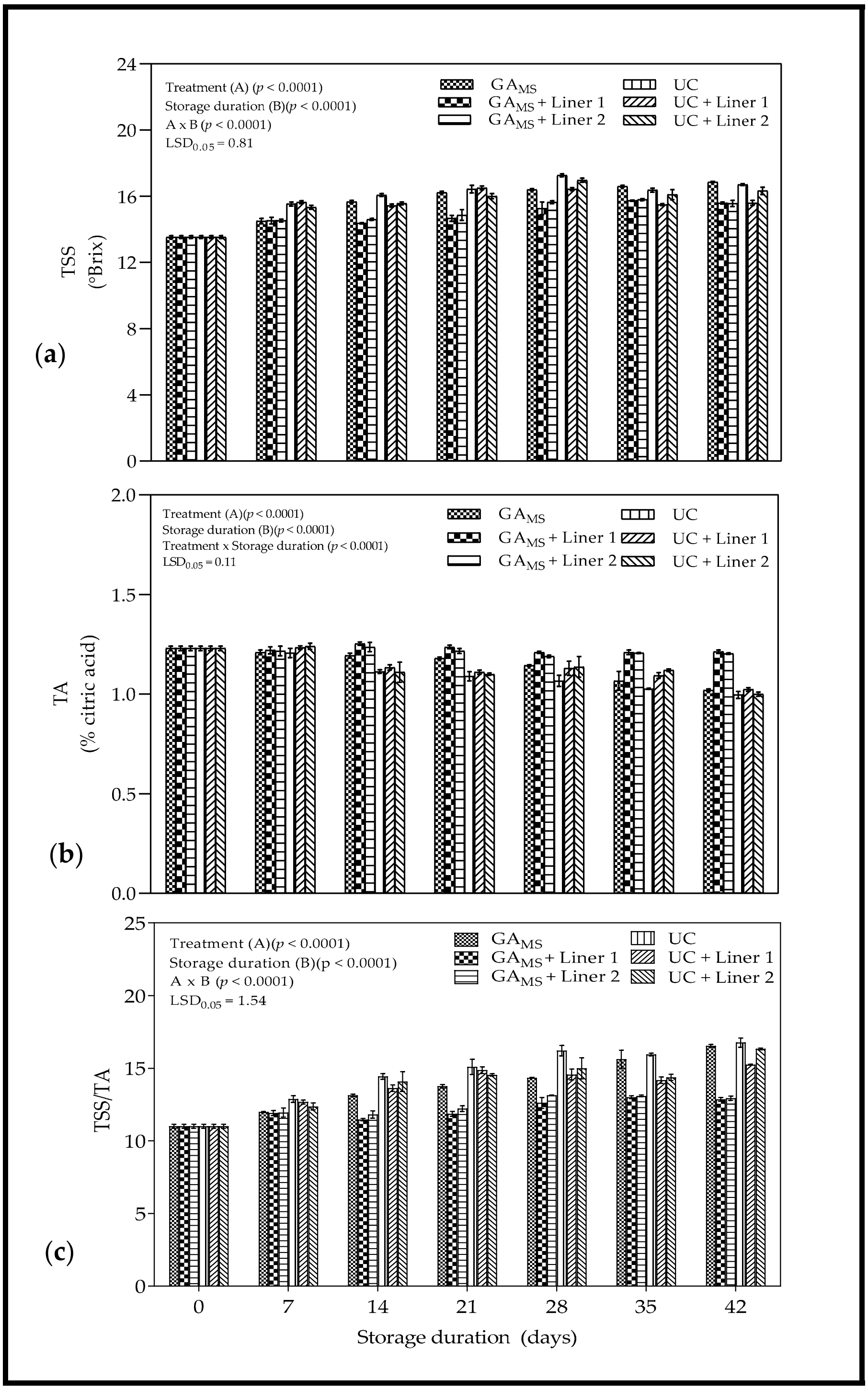

Figure 7. (**a**) Total soluble solids (°Brix), (**b**) titratable acidity (% citric acid) and (**c**) TSS/TA ratio of 'Wonderful' pomegranate coated and packaged in different polyliners and stored (5 ± 1 °C, 95 ± 2% RH) for 42 d. GA_{MS}—gum Arabic (0.5% *w*/*v*) and maize starch (0.5% *w*/*v*); Liner 1—Xtend® liner (20 µmm perforations); Liner 2—perforated liner (4 mm perforations); UC—uncoated fruit. $LSD_{0.05}$ represents least significant difference (p < 0.05).

3.4. Total Phenolic Content and Free Radical Scavenging Activity

An initial increase in TPC was observed from day 0 to day 28 for coated and uncoated fruit, followed by a gradual decline from day 35 to day 42 (Figure 8a). At the end of storage, the reduction in TPC was more pronounced in uncoated fruit (UC), whereas coated fruit packaged with or without packaging retained higher levels. In particular, treatments GA_{MS} + Liner 1 (84.68 mg GAE/100 mL PJ) and GA_{MS} + Liner 2 (68.16 mg GAE/100 mL PJ) showed the greatest retention of TPC during storage. There was no significant difference between TPC for treatments GA_{MS} and UC + Liner 2 on day 14, 35 and 42. Figure 8b shows the RSA for coated and uncoated pomegranate packaged with/without packaging during 42 d of storage. Besides the RSA measured on day 7, the highest values were recorded for treatments GA_{MS} + Liner 1 and GA_{MS} + Liner 2. On day 28, treatment GA_{MS} recorded significantly higher RSA values than UC + Liner 2. Subsequently, there was no significant difference between RSA values for treatments GA_{MS}, UC + Liner 1 and UC + Liner 2. After 42 d of storage, the order of magnitude for RSA was GA_{MS} + Liner 1 (3984. 80 ± 67.77 mM AAE/100 mL PJ) > GA_{MS} + Liner 2 (3820. 87 ± 265.92 mM AAE/100 mL PJ) > GA_{MS} (2928.77 ± 72.41 mM AAE/100 mL PJ) > UC (2833.46 ± 29.78 mM AAE/100 mL PJ) = UC + Liner 1 (2833.46 ± 29.78 mM AAE/100 mLPJ) = UC + Liner 2 (2833.46 ± 29.78 mM AAE/100 mL PJ).

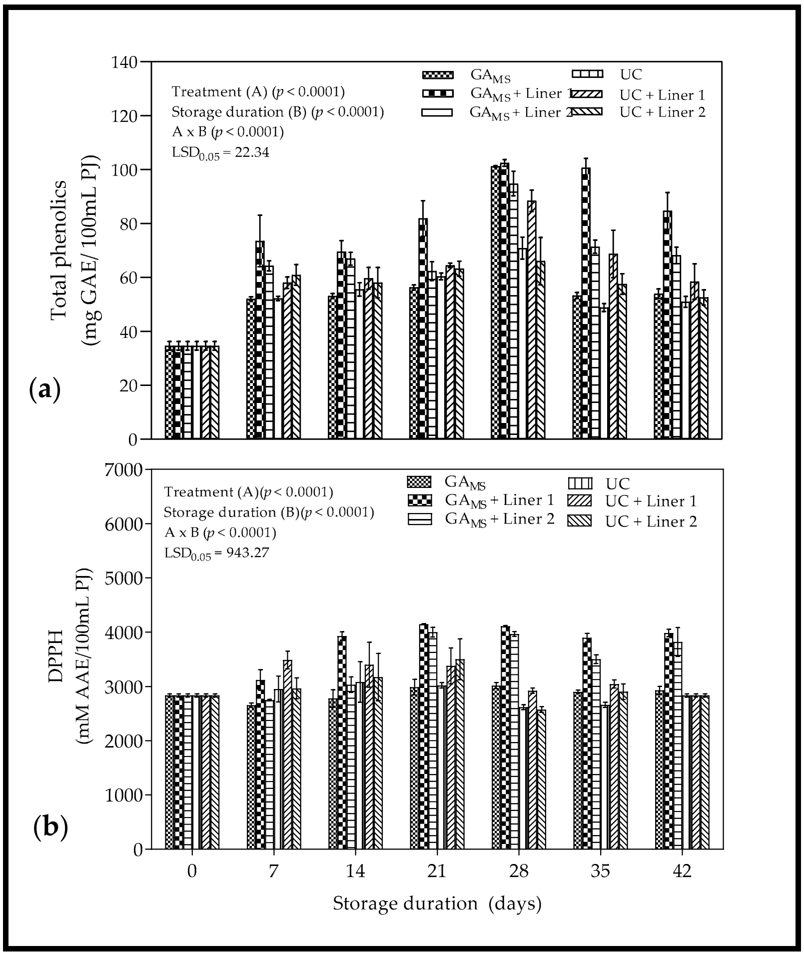

Figure 8. (**a**) Total phenolic content (mg GAE/100 mL PJ) and (**b**) radical scavenging activity (mM AAE/100 mL PJ) of 'Wonderful' pomegranate coated and packaged in different polyliners and stored (5 ± 1 °C, 95 ± 2% RH) for 42 d. GA_{MS}—gum Arabic (0.5% *w*/*v*) and maize starch (0.5% *w*/*v*); Liner 1—Xtend® liner (20 µmm perforations); Liner 2-perforated liner (4 mm perforations); UC—uncoated fruit. $LSD_{0.05}$ represents least significant difference ($p < 0.05$).

4. Discussion

4.1. Physiological Response

4.1.1. Weight Loss

Studies have shown that pomegranate fruit is susceptible to weight loss during cold storage [17,49]. Despite having a thick rind, the fruit has numerous natural pores on the peel surface, which become paths for excessive water loss after fruit has been harvested [12]. In the present study, GA_{MS} coating minimized weight loss in pomegranate fruit compared to uncoated samples. The results agree with Meighani et al. [48], who showed that resin wax coatings on 'Malase Torshe Saveh' pomegranates before cold storage (4.5 °C) significantly reduced weight loss as compared to uncoated fruit. In addition, packaging of 'Wonderful' pomegranates with polyliners during cold storage has been reported to reduce weight loss [13,64]. Internal packaging creates a modified atmosphere that minimizes water migration from the fruit to the environment, often leading to desiccation [21,26]. Therefore, in the present study, the combination of coatings and polyliners resulted in the least weight loss recorded after 42 days of storage (GA_{MS} + Liner 1 = 4.82%). Lesser weight loss was recorded for coated pomegranates packaged without polyliners (GA_{MS} = 8.77%) than uncoated fruit packaged with Liner 2 (UC + Liner 2 = 10.07%) which has larger perforations (≈4 mm) than Liner 1 (≈20 μmm), suggesting that GA_{MS} could be an alternative or replacement of polyliners with larger perforations (>4 mm).

4.1.2. Respiration Rate

Pomegranate fruit is classified as non-climacteric and exhibits low respiration rates that decline after harvest [65]. However, the respiratory pattern of the fruit can change during cold storage and shelf life when postharvest technologies are applied [60]. For instance, Elyatem and Kader [12] reported that increase in stress and the development physiological and pathological disorders in pomegranate fruit could result in higher respiration rates during cold storage.

In the present study, the application of coatings with or without polyliners exerted a significant ($p < 0.0001$) effect on the respiration rate of 'Wonderful' pomegranates. In the period between day 0 and day 21, there was an initial increase in respiration rate observed across all treatments. This could have been a physiological response of the fresh fruit of stress conditions imposed by cold storage temperature. Furthermore, increased respiration rate has been associated with depletion of sugars and organic acids as senescence is initiated in fresh fruit [47,66]. Studies have also attributed increment of respiration rate in 'Mollar de Elche' during storage to development of chilling injury [67] and the increasing peel porosity as storage time is extended [48]. Hussein et al. [62] observed an initial increase in respiration rate in bruised and non-bruised 'Wonderful' pomegranate during the first 4 weeks of cold storage (5 ± 0.5 °C and 92 ± 3% RH). However, in 'Ruby' and 'Bhagwa' pomegranates, Fawole and Opara [17] observed decrease in respiration rate in the first 4 weeks of storage (5 °C, 7 °C and 10 °C) followed by an unclear respiratory pattern as storage duration was extended.

Treatments GA_{MS}, GA_{MS} + Liner 1 and GA_{MS} + Liner 2 significantly reduced respiration rate compared to uncoated control (UC). Kawhena et al. [49] reported inter-related results with gum Arabic and starch-based coatings applied on 'Wonderful' pomegranates. Similarly, Meighani et al. [48] observed a lower respiration rate for 'Malase Torshe Saveh' pomegranates coated with chitosan and wax (carnauba and resin) coatings during cold storage (4.5 °C) and shelf life (20 °C). Lufu et al. [21] reported that respiration rate was highest in the 'Wonderful' pomegranates packaged with no-liner compared to fruit in perforated liners. This was attributed to decreased CO_2 concentration in 'Hicrannar' pomegranate fruit packaged with Xtend® and ZOEpac® polyliners during storage [68]. Polyliners limit gas permeability, as observed for fruit packaged with Liner 1 and Liner 2, which exhibited low respiration rates. Treatment GA_{MS} recorded a lower respiration rate than UC + Liner 2 for several periods during storage; however, the lowest respiration rate was recorded for fruit coated and packaged in polyliners for treatments GA_{MS} + Liner 1 and GA_{MS} + Liner 2.

The overall decrease in respiration rate across all treatments between day 21 and 42 could be explained by the reduction of metabolic activity in pomegranate as a response prolonged period of cold storage temperatures resulting in lower CO_2 production levels [17,69].

4.2. Physiological and Pathological Disorders

4.2.1. Shriveling

Shriveling is a physiological disorder known to occur in freshly harvested fruit as they lose turgidity and weight due to respiration and transpiration processes, which utilize sugar and water reserves without replacement [70]. Application of coatings on fresh fruit often limits moisture and gases movement through the surface pores and reduces the development of shriveling [42]. Shriveling occurs at approximately 3–10% weight loss in fresh fruit [70]. In the present study, visible symptoms were observed after 21 d in treatments with weight loss in the range of 3.33–13.33% across all treatments. While treatment GA_{MS} reduced weight loss, shriveling was effectively inhibited when the fruit was packaged with polyliners (GA_{MS} + Liner 1 and GA_{MS} + Liner 2). This suggests that effective control of shriveling was only achieved when coated fruit was packaged with polyliners.

4.2.2. Decay Incidence and Internal Decay

The results corroborate with Palou et al. [71], who observed an increase in decay incidence as storage duration was extended for 'Mollar de EIche' pomegranates. However, in the present study, coating fruit and packaging with polyliners (GA_{MS} + Liner 1 and GA_{MS} + Liner 2) minimized decay. The combined effect of coatings and polyliners resulted in resistance to decay development in pomegranate fruit. Coatings form a semi-permeable barrier to micro-organisms which may limit infection during cold storage. Similarly, polyliners reduce direct infection with microbes from the external environment and reduce fruit decay incidence [72,73]. Lufu et al. [21] outlined that losses due to decay were minimized when pomegranate fruit were packaged with micro-perforated Xtend® and macro-perforated (4 mm) liners.

4.3. Physicochemical Properties

4.3.1. Color

Color of fresh produce is regarded as an important factor contributing to consumer acceptance [74]. Freshly harvested fruit often has good appearance quality associated with more vibrant color and glossiness. These attributes are related to moisture content and wax deposition and can be significantly affected by postharvest treatments [47,48]. For instance, studies showed that application of some edible coatings or wax imparted a glossy appearance on the surface of 'Tommy Atkins' mango [75], 'Valencia' oranges [76] and 'Malase Torshe Saveh' pomegranates [48].

In this study, between day 0 to day 28, the application of coatings and packaging minimized the change in lightness of fruit. However, in the same period, lightness increased in uncoated fruit without packaging (UC). Since L* values are determined on the light–dark axis, increasing values indicated brighter/less-dark samples. The results corroborated with Mantilla et al. [77], who observed lower lightness values for fresh-cut pineapples coated with sodium alginate-based coatings on day 7 out of 15 of cold storage mainly due to the thickness of the coating. In contrast, Chiumarelli et al. [75] reported that cassava starch and citric acid-based coatings enhanced the lightness of fresh cut mangoes by improving the brightness of fruit surface during 15 d of cold storage. The effect was attributed to the citric acid of the coating solutions, which acted as an antibrowning agent by delaying the enzymatic mediated browning of fresh produce [78]. Selcuk and Erkan [68] also demonstrated higher lightness values for pomegranate fruit packaged in Xtend® and ZOEpac® liners than those without packaging during storage and shelf-life. Based on the results in this study, coated fruit with/without packaging minimized the change in lightness of fruit for large periods of storage, whereas lightness increased in uncoated fruit.

The loss in redness of fruit between day 21 and day 35 could have coincided with increased lightness in uncoated samples. During this period, fruit coated and packaged with Liner 1 (GA_{MS} + Liner 1) mostly maintained higher positive a* values than uncoated fruit (UC). The characteristic red color or intense pigmentation of pomegranate has been linked to the accumulation of anthocyanins [5,22,46]. In general, changes in red color in fresh fruit during cold storage are associated with enzymatic biosynthesis or degradation of anthocyanins. Treatment GA_{MS} + Liner 1 could have minimized the degradation or biosynthesis of anthocyanins, thereby reducing changes in a* values. Between day 14 and day 35, the application of coatings with packaging resulted in higher recorded C* values than uncoated fruit without packaging (UC). This suggests that for extended periods of storage, the tone of the color was more intense/redder for coated fruit with packaging compared to uncoated fruit without packaging. Similarly, for h° values, higher values were recorded for the fruit coated and packaged in polyliners. The treatment combination (coatings and polyliners) appeared to achieve better color retention than either coating or packaging materials individually.

4.3.2. Total Soluble Solids and Titratable Acidity

An increase in TSS content of fresh fruit is often associated with the hydrolysis of starch to simple sugars [79,80]. Furthermore, moisture loss in fresh fruit leads to the concentration of the soluble solids observed as an increase as storage duration is extended. In the present study, the TSS content increase agrees with the observation by Arendse et al. [80] for 'Wonderful' pomegranates stored at different temperatures (7.5 and 10 °C) for 5 months. While GA_{MS} recorded lower TSS than UC + Liner on day 7 and day 28, the effect was greater for treatments GA_{MS} + Liner 1 and GA_{MS} + Liner 2. Treatments GA_{MS} + Liner 1, GA_{MS} + Liner 2 could have minimized increase in TSS as compared to uncoated fruit (UC) by slowing down respiration and metabolic activities. Similarly, Meighani et al. [48] reported that chitosan and wax-based coatings delayed physiological processes leading to change in TSS content, including respiration and hydrolysis of starch.

The decrease in TA during cold storage is often related to the consumption of organic acids as substrates for the respiratory metabolism in detached fresh fruits [48]. The change in TA content was mostly retarded by subjecting fruit to treatments GA_{MS} + Liner 1 and GA_{MS} + Liner 2. This suggests that the treatments may have reduced respiratory metabolism and subsequently minimizing loss of TA content. Interrelated results were reported by Selcuk and Erkan [68] for 'Hicrannar' pomegranates packaged with polyliners which recorded higher values of TA compared to the unpackaged fruit. Likewise, the application of chitosan and wax-based coatings on 'Malase Torshe Saveh' pomegranates minimized the change in TA during 120 d at 4.5 °C and 3 d additional at 20 °C [48]. The general increase in TSS/TA in all treatments can be attributed to the overall increase in TSS and decrease in TA. Application of coatings and polyliners significantly reduced changes in both TSS and TA as previously reported in pomegranate fruit during cold storage [13].

4.4. Total Phenolic Content and Radical Scavenging Activity

4.4.1. Total Phenolic Content

The increasing pattern in TPC observed from day 0 to day 28 corroborates with studies reported by Arendse et al. [81] and Fawole and Opara [17] for cold stored 'Wonderful' pomegranate. The authors attributed the increase to continued biosynthesis and accumulation of anthocyanins induced when fruit were subjected to cold storage temperatures [46]. The decreasing pattern observed between day 35 and day 42 could be related to phenolic degradation due to enzymatic activities of polyphenol oxidase and peroxidase [17,82]. Sayyari et al. [83] similarly observed decrease in TPC in 'Mollar de Elche' pomegranate fruit during 84 days of cold storage (2 °C).

A decreasing trend in the TPC of untreated pomegranate fruit during cold storage has been reported in several studies [13,17,27]. The decrease in TPC is related to phenolic degradation due to enzymatic activities of polyphenol oxidase and peroxidase due to low temperature stress [17,82]. Application of treatments GA_{MS} + Liner 1, GA_{MS} + Liner 2 showed the greatest response in fruit to reduce the loss of TPC during storage. Application of coatings on fresh fruit and packaging with polyliners creates abiotic stress and modifies metabolism, resulting in secondary metabolites including phenolic compounds [13,84,85]. In particular, under stress conditions, the enzyme phenylalanine ammonia lyase (PAL) is implicated in the synthesis of phenolic compounds for protection against oxidative attacks [82].

In the present study, the results agreed with Meighani et al. [48], who observed TPC maintenance in 'Malase Torshe Saveh' pomegranates coated with chitosan and carnauba wax coatings during storage. However, Mphahlele et al. [13] showed that storage of 'Wonderful' pomegranates in open-top cartons with ZOEpac® polyliners did not prevent degradation of phenolics [13]. Similarly, Selcuk and Erkan [27] showed that 'Hicaznar' pomegranates without packaging recorded higher TPC than the fruit stored in Xtend® and ZOEpac® polyliners during storage at 6 °C or after 3 d at 20 °C. Therefore, based on our findings, the combination effect of coatings and plastic packaging maintained the TPC of PJ extracted from 'Wonderful' pomegranate at different intervals after cold storage and shelf life.

4.4.2. Radical Scavenging Activity

Radical scavenging activity against free radicals in fresh fruit is usually associated with the accumulation of phenolic compounds, which is catalyzed by PAL activity [84]. Low temperature and oxygen conditions often stimulated the production of primary and secondary metabolites such as polyphenols, including flavonoids, anthocyanins and hydrolysable tannins [17,83]. However, a decrease in TPC has been reported for pomegranate fruit such as 'Mollar de Elche' and 'Bhagwa' during cold storage (2–7 °C) [17,83]. Similarly, phenolic metabolites can decrease when fresh fruit is stored in conditions of high CO_2 concentration [86]. In this study, the pattern of change of TPC was related with RSA, with fruit coated and packaged in polyliners recording higher RSA than uncoated fruit. This can be attributed to the combined effect of coatings and polyliners in altering the internal atmosphere of fresh fruit, initiating secondary responses which affect metabolic activity and antioxidant mechanism [87]. Application of coatings has been shown to improve the antioxidant status of pomegranate fruit [49]. Similarly, Mphahlele et al. [13] observed a two-fold increase in RSA for 'Wonderful' pomegranates packaged in ZOEpac polyliners after 4 months storage at 7 ± 0.5 °C. The results suggested that the combined effect of coatings and plastic packaging produced a higher RSA than either coating or packaging only.

5. Conclusions

Edible coatings present a promising biodegradable postharvest technology and potential alternative to plastic polyliners to extend the storage and shelf life of pomegranate fruit. In the present study, the combination of gum Arabic-maize starch coating (GA_{MS}) and polyliners (Xtend® and 4 mm perforated liner) reduced weight loss, respiration rate and maintained the overall quality of 'Wonderful' pomegranate. However, coated packaged without polyliners (GA_{MS}) performed better than uncoated fruit packaged with 4 mm perforated polyliner in reducing weight loss, respiration rate and maintaining total soluble solids content. Given the high cost of polyliners, gum Arabic-maize starch coatings could be a cheaper and biodegradable alternative for 'Wonderful' pomegranates packaged with 4 mm perforated liners. However, the synergistic activity of coatings and polyliners presented better packaging outcomes and overall postharvest quality of fruit. Therefore, future research will focus on optimizing edible coatings with components such as lipids (fatty acids and acetylated monoglycerides) and emulsifiers to improve functional properties and maintain postharvest storage and shelf life of pomegranate. Furthermore, studies should explore the effects of the combination of optimized edible coatings with either bio-based or biodegradable plastic packaging materials made from recyclable sources, which present more sustainable packaging alternative technologies in fresh fruit.

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