Applied Food Research 3 (2023) 100289

Contents lists available at ScienceDirect

Applied Food Research

journal homepage: www.elsevier.com/locate/afres

4-hexylresorcinol and sodium metabisulphite-based edible coatings for avocado shelf-life extension

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ARTICLE INFO

Keywords:
Avocado
Alginate
4-hexylresorcinol
Sodium metabisulphite
Edible packaging
Shelf-life
Antioxidant

ABSTRACT

The short shelf-life of avocados poses problems in the food supply chain, including economic losses due to food waste. This study aimed at developing a new active packaging with antioxidant potential to extend the shelf life of *Hass* avocados. The fruits were immersed in the solutions of 4-hexylresorcinol (4-HR, 250 and 500 mg/L) and sodium metabisulphite (SMBS, 1250 and 2500 mg/L), labelled as additive-only samples. Another set of samples was prepared by coating the fruits with sodium alginate films (10 g/L) containing the additives (alginate-coated samples). The samples were stored for 10 days at 25 ± 1 °C and 60% RH. Weight loss, total soluble solids (TSS) content, pH, firmness and bioyield point (BYP), internal and external colour and appearance, and microbial load of the samples were investigated on days 1, 5 and 10. Alginate-coated samples had lower weight loss and less increase in the total soluble solids (TSS) and pH values during storage. Firmness values remained similar for all samples from day 1 to 10, regardless of the coating used. Additive-only samples retained the bioyield point (BYP) values, whilst there was a decrease in the alginate-coated samples over 10 days. No differences were observed in the colour parameters (L^*, a^* and b^*) between the additive-only and alginate-coated samples; the latter had a better internal and external appearance. Colour stability was slightly higher when 4-HR was added to alginate coatings than 4-HR as a standalone additive treatment. The microbial enumeration and visual appearance showed that the presence of alginate in the coating had an antimicrobial impact (no surface microbial growth). Alginate-based coatings can be a promising sustainable alternative for maintaining avocado quality during storage.

1. Introduction

Avocado (*Persea americana*) is a climacteric fruit with high nutritional value, and its production and consumption occur on a global scale (Araújo et al., 2018; Bill et al., 2014; Zafar & Sidhu, 2018). The short shelf life of avocados, governed by enzymatic browning, oxidative processes, and microbial spoilage (Aguiló-Aguayo et al., 2014; Garcia & Davidov-Pardo, 2021a), poses problems in the food supply chain, including economic losses due to food waste. Post-harvest life of avocados at 4–13 °C is 14–28 days, with minimum oxygen (O_2) and carbon dioxide (CO_2) tolerance of 2.0 and 10.0%, respectively (Nor & Ding, 2020). Storage at room temperature reduces shelf life to 5 to 7 days (Araújo et al., 2018; Munhuweyi et al., 2020). Ripening occurs after harvesting; several changes affecting fruit quality may occur during this stage. The increase in the respiration rate and ethylene production leads to the cell wall's breakdown, resulting in O_2 entering the fruit as water and CO_2 are released. Pectinases contribute to the breakdown of the cell wall, accelerating the loss of moisture and firmness (Araújo et al., 2018; Garcia & Davidov-Pardo, 2021a). Therefore, preserving the fruit quality and preventing deterioration during shelf-life is essential.

Edible films and coatings, when used for packaging, create a barrier between the packaged food and its immediate environment (i.e., oxygen). The functionality of coatings can be extended by incorporating ingredients with antioxidant and antimicrobial properties such as phenolics, essential oils and nanoparticles (Amin et al., 2021; Garcia & Davidov-Pardo, 2021a; L. Kumar et al., 2021; Nair et al., 2020). Many studies attempted to use non-active or active coatings for avocado shelf-life extension, which are discussed in detail elsewhere (Garcia & Davidov-Pardo, 2021a). The ingredients active films utilised included pectin and candelilla wax (Aguirre-Joya et al., 2017), sodium alginate with the yeast *Meyerozyma caribbica* (Iñiguez-Moreno et al., 2020, 2021), chitosan and gum arabic-based coating with added zinc oxide (ZnO) nanoparticles (Le et al., 2021), chitosan and carboxymethyl cellulose coating embedded with phenylalanine (Saidi et al., 2021) and coatings made of zein, zein nanoparticles and ε-polylysine (Garcia et al., 2022).

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https://doi.org/10.1016/j.afres.2023.100289
Received 3 January 2023; Received in revised form 4 March 2023; Accepted 6 March 2023
Available online 11 March 2023

Alginate, a brown seaweed extract, is a naturally occurring, indigestible, non-toxic, and biodegradable polysaccharide widely used as a coating material (Amin et al., 2021; Parreidt et al., 2018). Alginate coatings and films form a semi-permeable membrane. They have been used to preserve various foods, including fresh fruits and vegetables, meats, poultry, seafood and fish (Bonilla et al., 2012; Nair et al., 2020; Parreidt et al., 2018). They provide a barrier to O_2 and CO_2, thus reducing the rate of oxidation reactions (Corbo et al., 2015), leading to the retention of moisture, total soluble solids and nutrients, and preserving the appearance of the coated food.

Sodium metabisulphite (SMBS) is a food preservative [E-number (E223)] with antioxidant and antimicrobial properties (Silva & Lidon, 2016). Sulphites have been used to inhibit enzymatic browning in avocados (Gómez-López, 2002) and avocado jelly (López-Ramírez & Duarte-Sierra, 2020). Sulphites and sulphur dioxide are among the major allergens in food, and when present at concentrations greater than 10 mg/kg (ppm), they need to be declared on the label (FSA, 2020). Whilst preventing enzymatic browning and extending product shelf life, sulphites may cause adverse reactions in sensitive individuals with pre-existing allergies like asthma and hay fever (Asif et al., 2020; Madan et al., 2007). Therefore, the food industry attempts to find alternatives for anti-browning and antioxidant compounds to produce sulphite-free foods.

4-hexylresorcinol (4-HR, chemical formula $C_{12}H_{18}O_2$), a phenolic lipid considered an antioxidant (E586), competes with the polyphenols in foods and acts as a substrate for polyphenol oxidase, inhibiting enzymatic browning. It prevents melanosis (formation of dark pigments known as black spots) in prawns and crustaceans (Galvão et al., 2017; Martínez-Álvarez et al., 2005; Martínez-Alvarez et al., 2007; Montero et al., 2004; Slattery et al., 2009). 4-HR has a long history of use in pharmaceutical applications with no systemic toxicity and is authorised as a safe food additive to prevent browning reactions in fresh shellfish and crustaceans (frozen and deep-frozen) as an alternative to sulphites (Iyidoğan & Bayindirli, 2004; Silva & Lidon, 2016). According to European Food Safety Authority (EFSA, 2014), the maximum allowable limit of 4-HR residue in crustaceans is 2 mg/kg (2 ppm). Several studies have examined the effectiveness of 4-HR in preserving fruits and vegetables such as mango puree (Guerrero-Beltrán et al., 2005), pears (Arias et al., 2007, 2008, 2011; Oms-Oliu et al., 2006), eggplants (Ghidelli et al., 2014), apples (Perez-Gago et al., 2006; Ribeiro et al., 2020) and fresh-cut kiwis (Bhat et al., 2021). However, similar studies on avocados are scarce. In a study on avocado slices, 4-HR (0.025 M) was incorporated into a gellan gum coating (together with D-isoascorbate, L-glutathione and sodium hexametaphosphate) followed by 8 h storage at 25 °C (Mendoza-Gómez et al., 2017). The study measured the polyphenol oxidase (PPO) activity along with colour, sensory and microbiological analysis. The individual effect of 4-HR did not significantly reduce the in vitro PPO activity, and the presence of 4-HR in the formulation influenced the flavour of the samples.

The present study aims to investigate the efficiency of a novel active packaging with antioxidant potential to extend the shelf-life of avocados. There is a gap in academic literature reviewing the role and use of 4-HR and SMBS in edible coatings to maintain the quality of whole avocados. Thus, this study explores the effect of those additives (used alone and when incorporated into alginate coatings) on the physicochemical properties of avocados during storage.

2. Materials and methods

2.1. Materials

Ready-to-eat *Hass* avocados (origin: Israel, time from harvesting to packaging: 10 h, travel time to the UK: 20 days under a controlled temperature of 5 °C and modified atmosphere of 6–8% CO_2, average dry matter content: 29.98%) that were free from infection and physical defects and had similar maturity, colour and size were a contribution from Greencell Ltd (Spalding, Lincolnshire, UK). Ten samples were produced using two additives (4-HR and SMBS) and with or without adding sodium alginate. 4-HR was a kind contribution from Xyrex Ltd (Glasgow, UK). SMBS was purchased from APC Pure (Cheshire, UK). Sodium alginate was purchased from Special Ingredients Ltd (Chesterfield, UK). The avocado samples were labelled as follows: untreated avocado [C], avocado coated with sodium alginate [AC], avocado coated with sodium alginate containing 4-HR (250 and 500 mg/L) and SMBS (1250 and 2500 mg/L) [AHR250, AHR500, AS1250 and AS2500] and without alginate [HR250, HR500, S1250 and S2500] (See Table 1 for a more detailed description of the samples).

Table 1
Sample descriptions and codes.

Coating/additive used	Sample description	Sample code
No coating/no additive	Control	C
Alginate/no additive	Alginate control	AC
Additive only	4-hexylresorcinol (250 ppm)	HR250
	4-hexylresorcinol (500 ppm)	HR500
	Sodium metabisulphite (1250 ppm)	SMBS1250
	Sodium metabisulphite (2500 ppm)	SMBS2500
Alginate/additive	4-hexylresorcinol (250 ppm)	AHR250
	4-hexylresorcinol (500 ppm)	AHR500
	Sodium metabisulphite (1250 ppm)	ASMBS1250
	Sodium metabisulphite (2500 ppm)	ASMBS2500

2.2. Preparation of coating solutions

The edible coating solution was prepared by mixing 10 g of sodium alginate powder (Li et al., 2019; Zhang et al., 2016) and 2 g of glycerol as a plasticiser in distilled water to make a total volume of 1000 ml. The solution was stirred at room temperature for 4 h using an overhead stirrer (IKA® England Ltd, Oxford, UK). After being kept at 4 °C overnight for complete rehydration, it was equilibrated at room temperature for 2 h before use. Different additives (4-HR and SMBS) were added (250 and 500 mg/L for 4-HR and 1250 and 2500 mg/L for SMBS) to the resultant coating solution using the overhead stirrer. The concentration of the applied antioxidant was an average of what has been reported in the literature for 4-HR (de Corato, 2019; Dong et al., 2000; Qian et al., 2015) and SMBS (Anaya-Esparza et al., 2018; Utama et al., 2021). Another set of coating solutions was prepared using distilled water only (no alginate) with the same additives to ascertain the effect of alginate on the parameters studied. The experiments were repeated on two different occasions.

2.3. Application of the coating

Whole avocados (with the skin) were numbered using a permanent marker to use the same samples at every time point for the weight loss measurement. The avocados were dipped in the additive solutions for 30 min, as per the manufacturer's recommendation, and the alginate solutions for 5 min as an average of the dipping times range suggested in the literature (Kumar et al., 2018; Kumari & Nikhanj, 2022; Maftoonazad et al., 2008). The samples were allowed to dry at room temperature for 2 h before being transferred into a controlled cabinet (25 ± 1 °C, 60% RH) and stored for 10 days. The cabinet was illuminated with an LED lamp to give a light intensity of 2000 Lux/m^2 to match the light intensity in the retail environment. Samples were collected immediately after preparation (Day 1) and after 5 and 10 days of storage. The storage time was decided after reviewing the available literature (Aguirre-Joya et al., 2017; Garcia et al., 2022; Iñiguez-Moreno et al., 2021; Le et al., 2021). Five avocados per sample were collected at each time point for analysis.

2.4. Weight loss

The initial weight of the samples was recorded. After coating, the samples were allowed to air dry before being re-weighed. Sample weight was recorded after 5 and 10 days of storage, and the difference was calculated for each avocado ($n = 3$). The total weight loss was considered the difference between the initial and final weight. The results were expressed as the per cent weight loss from the starting weight per the AOAC method (AOAC, 1994).

2.5. Total soluble solids (TSS) content

Avocado flesh was scooped out with a spatula, mashed until smooth and placed onto a digital refractometer (Hanna Instruments Sucrose Refractometer, Bedfordshire, UK). The digital refractometer was calibrated with distilled water before use. Three TSS measurements were taken from each sample ($n = 3$).

2.6. pH

Avocado flesh (10 g) and distilled water (90 ml) were mixed using a hand blender at a low speed. The pH of the samples was determined using a pH metre (Hanna Instruments, Bedfordshire, UK) after being calibrated at 18 °C using buffer solutions (pH 4, 7 and 10). Three pH measurements were taken from each sample ($n = 3$).

2.7. Texture measurements

Firmness and bioyield point (BYP) of the samples were measured at room temperature (21 ± 1 °C) using a TA texture analyser (TA-XTplus Texturometer; Stable Micro System, Vienna Court, UK) equipped with a 500 N load cell and coupled with an SMS P/2 small cylinder probe (2 mm diameter). The probe was selected as recommended by the manufacturer. The cylindrical probe was stably inserted into the unpeeled avocado to a depth of 8 mm at a speed of 1 mm s^{-1}. The measurements were taken at five different locations per fruit ($n = 3$), and the values were averaged.

BYP is the point at which an increase in deformation is observed with a decrease or no change of force. During this phase of elastic deformation, cells start to fail but without rupture (reversible). Beyond the BYP, the macrostructure of the specimen begins to fail, leading to the final rupture (irreversible). Firmness was measured as the force needed to puncture the fruit's skin and cause a complete and non-reversible deformation of the fruit flesh (Lu et al., 2005; Sahin & Sumnu, 2006). Both firmness and BYP were measured in Newton (N).

2.8. Colour measurements and visual appearance

External (skin) colour measurements of whole avocados and internal colour measurements of avocado halves were taken ($n = 5$) using a Chroma Meter (illuminant D65; 8-mm-diameter aperture, 2° standard observer; CR-400; Konica-Minolta Corp., Tokyo, Japan) to determine the L* value (lightness or brightness), a* value (redness or greenness) and b* value (yellowness or blueness). The colourimeter was warmed up for 20 min and calibrated with a white tile standard. Three avocados were used, measurements were taken from five locations on the same avocado (both for external and internal colour), and the average of L*, a* and b* values were calculated. Chroma (C*) values were also calculated by Eq. (1) to investigate any correlation of fruit colour with other parameters studied.

$$C* = \sqrt{(a*)^2 + (b*)^2} \quad (1)$$

For the visual appearance, the photographs of the external skin and internal flesh were taken during the colour analysis on days 1, 5 and 10.

2.9. Microbiological analysis

Total Viable Count (TVC) and mould and yeast count (MYC) were conducted. Avocados were homogenised using a sterile mortar and pestle. Homogenates (25 ± 1 g) were weighed and placed in sterile stomacher bags, to which 225 ml Buffered Peptone Water (BPW) was added. Serial dilutions were conducted in 9 ml BPW bottles. A volume of 0.1 ml was deposited on Plate Count Agar (PCA) and Potato Dextrose Agar (PDA) plates and spread. Duplicate plating was carried out. Plates were rested for 15 min, then inverted and incubated (30 °C, 72 h for PCA and 25 °C, 5 days for PDA). Colonies were counted with a manual plate counter. Plates with <300 colonies (PCA) and 50 to 100 colonies (PDA) were used for calculations.

2.10. Statistical analysis

Data were analysed using a complete randomised block design with two replications. All results were expressed as mean ± standard deviation (SD). The data were analysed using IBM SPSS Statistics Version 26 (IBM, 2019). General linear model (GLM) and univariate procedures were used to ascertain significant differences with Tukey *post hoc* testing of subsets. Significant differences were determined at the $P < 0.05$ level.

3. Results and discussion

3.1. Weight loss

One of the major problems with avocados post-harvest is rapid water loss, which is directly related to weight loss. The application of coatings may hinder it to a different extent. In the current study, longer storage time resulted in more significant weight loss in all samples ($P < 0.05$) regardless of the coating used (Fig. 1). The control sample had a weight loss of 9.68 ± 1.29% on day 5 and 30.1 ± 10.26% on day 10. There was no significant weight loss difference between the control (C) and additive-containing samples on days 5 and 10. Compared to their additive-only counterparts, the samples coated with alginate showed less weight loss after day 10 (ranging from 12.80 to 17.64% vs. 23.90 to 34.13% for additive-only samples). Still, the difference was only significant for HR250 and AHR250. Maftoonazad and Ramaswamy (2008) reported that a pectin-based coating resulted in a significant difference in weight loss of *Hass* avocados during 7 days of storage at 20 °C (9.1% weight loss in coated samples vs. 11.5% in control, $P < 0.01$). Iñiguez-Moreno et al. (2020) found that *Hass* avocado control samples lost 3.7% more weight than avocados coated with sodium alginate and yeast (approx. 8%) during storage at 25 °C for 15 days ($P < 0.05$). The weight loss in the current study seemed higher than in those studies. The discrepancy could be due to different experimental conditions (i.e., RH and coatings) or different maturity stages of avocados, which, in addition to the cultivar, determine the amount of water loss in avocados (Bill et al., 2014).

3.2. Total soluble solids (TSS) content

The control sample (C) had the lowest TSS content at 8.88 ± 1.73 on day 1, which increased to 12.98 ± 2.13 on day 10 (Table 2). The TSS content of the control sample was comparable to what was reported by Aguiló-Aguayo et al. (2014) (8.56 ± 0.50). As the ripening progresses, TSS levels (°Brix) tend to increase because of the conversion of polysaccharides into sugars and organic acids into short-chained acids (Salameh et al., 2022; Taiti et al., 2015).

Samples coated with alginate had lower TSS than the control and those only coated with additives at each time point, with samples coated with only 4-HR at 500 mg/L (HR500) having the most significant TSS on day 10. Several studies with avocados found that storage increased the TSS value, occurring faster under ambient conditions (Kassim &

Table 2
Total soluble solids (°Brix), pH value and texture parameters [firmness (N) and bioyield point (N)] of untreated avocado (C), avocado coated with alginate (10 g/L) (AC), avocados immersed in 4-Hexylresorcinol (250 and 500 mg/L) and sodium metabisulphite (1250 and 2500 mg/L) solutions without alginate (HR250, HR500, S1250 and S2500) or with 10 g/L alginate (AHR250, AHR500, AS1250 and AS2500) during 10 days of storage.

Days of storage	C	AC	HR250	HR500	S1250	S2500	AHR250	AHR500	AS1250	AS2500	*P* value
TSS (°Brix)											
Day 1	$8.88 \pm 1.73^{b}{}_{B}$	$9.89 \pm 1.17^{ab}{}_{B}$	$10.48 \pm 0.94^{a}{}_{B}$	$10.62 \pm 1.09^{a}{}_{B}$	$9.72 \pm 1.44^{ab}{}_{B}$	$10.23 \pm 1.38^{ab}{}_{B}$	$10.46 \pm 1.85^{a}{}_{A}$	$9.96 \pm 0.91^{ab}{}_{A}$	$9.88 \pm 1.04^{ab}{}_{A}$	$10.39 \pm 1.30^{a}{}_{B}$	**0.006***
Day 5	$9.98 \pm 1.38^{ab}{}_{B}$	$10.20 \pm 1.43^{ab}{}_{B}$	$11.31 \pm 1.99^{a}{}_{AB}$	$10.44 \pm 0.89^{ab}{}_{B}$	$11.23 \pm 1.11^{a}{}_{A}$	$11.57 \pm 1.84^{a}{}_{AB}$	$10.36 \pm 1.91^{ab}{}_{A}$	$9.94 \pm 1.82^{ab}{}_{A}$	$10.98 \pm 2.20^{ab}{}_{A}$	$9.46 \pm 0.90^{b}{}_{B}$	**0.001***
Day 10	$12.98 \pm 2.13^{ab}{}_{A}$	$11.38 \pm 1.20^{abcde}{}_{A}$	$12.37 \pm 1.72^{abc}{}_{A}$	$13.07 \pm 2.04^{a}{}_{A}$	$10.97 \pm 2.17^{bcde}{}_{AB}$	$12.08 \pm 2.24^{abcd}{}_{A}$	$10.74 \pm 1.37^{cde}{}_{A}$	$10.29 \pm 2.00^{de}{}_{A}$	$9.94 \pm 1.53^{e}{}_{A}$	$11.75 \pm 2.17^{abcde}{}_{A}$	**0.000***
P value	**0.000***	**0.002***	**0.004***	**0.000***	**0.017***	**0.012***	0.794	0.773	0.091	**0.000***	
pH Value											
Day 1	$7.15 \pm 0.18^{a}{}_{B}$	$7.00 \pm 0.20^{ab}{}_{B}$	$6.98 \pm 0.15^{ab}{}_{B}$	$6.96 \pm 0.18^{ab}{}_{B}$	$6.95 \pm 0.18^{ab}{}_{B}$	$7.03 \pm 0.22^{ab}{}_{B}$	$7.07 \pm 0.21^{ab}{}_{A}$	$6.90 \pm 0.16^{b}{}_{A}$	$7.04 \pm 0.25^{ab}{}_{A}$	$6.93 \pm 0.26^{ab}{}_{A}$	**0.015***
Day 5	$7.18 \pm 0.10^{a}{}_{AB}$	$6.93 \pm 0.29^{bcd}{}_{B}$	$7.05 \pm 0.13^{ab}{}_{B}$	$6.96 \pm 0.16^{bc}{}_{B}$	$6.93 \pm 0.09^{bcd}{}_{B}$	$6.89 \pm 0.10^{bcd}{}_{B}$	$6.75 \pm 0.27^{d}{}_{B}$	$6.80 \pm 0.11^{cd}{}_{A}$	$6.88 \pm 0.27^{bcd}{}_{A}$	$6.81 \pm 0.15^{cd}{}_{A}$	**0.000***
Day 10	$7.35 \pm 0.34^{ab}{}_{A}$	$7.33 \pm 0.42^{ab}{}_{A}$	$7.42 \pm 0.33^{a}{}_{A}$	$7.21 \pm 0.25^{abc}{}_{A}$	$7.48 \pm 0.37^{a}{}_{A}$	$7.40 \pm 0.31^{a}{}_{A}$	$6.48 \pm 0.28^{e}{}_{C}$	$6.56 \pm 0.23d^{e}{}_{B}$	$6.90 \pm 0.15^{cd}{}_{A}$	$6.98 \pm 0.78^{bc}{}_{A}$	**0.000***
P value	**0.027***	**0.001***	**0.000***	**0.000***	**0.000***	**0.000***	**0.000***	**0.000***	0.072	0.538	
Firmness (N)											
Day 1	$245.3 \pm 120.2^{ab}{}_{A}$	$259.8 \pm 109.3^{ab}{}_{B}$	$246.2 \pm 102.4^{ab}{}_{AB}$	$227.5 \pm 99.1^{b}{}_{A}$	$293.4 \pm 94.3^{ab}{}_{A}$	$327.4 \pm 129.0^{ab}{}_{A}$	$241.3 \pm 85.5^{ab}{}_{AB}$	$286.5 \pm 180.5^{ab}{}_{A}$	$345.5 \pm 178.9^{a}{}_{A}$	$319.6 \pm 183.5^{ab}{}_{A}$	**0.005***
Day 5	$267.4 \pm 154.7^{bc}{}_{A}$	$411.4 \pm 142.7^{a}{}_{A}$	$237.9 \pm 141.8^{c}{}_{B}$	$265.8 \pm 164.3^{bc}{}_{A}$	$295.1 \pm 99.9^{abc}{}_{A}$	$323.0 \pm 161.1^{abc}{}_{A}$	$313.1 \pm 149.2^{abc}{}_{A}$	$330.6 \pm 135.8^{abc}{}_{A}$	$304.0 \pm 130.1^{abc}{}_{A}$	$381.4 \pm 183.2^{ab}{}_{A}$	**0.001***
Day 10	$233.6 \pm 138.0^{ab}{}_{A}$	$284.5 \pm 142.3^{ab}{}_{B}$	$325.6 \pm 142.7^{ab}{}_{A}$	$311.0 \pm 185.4^{ab}{}_{A}$	$251.3 \pm 141.93^{ab}{}_{A}$	$352.0 \pm 185.4^{a}{}_{A}$	$212.7 \pm 118.4^{b}{}_{B}$	$262.5 \pm 173.7^{ab}{}_{A}$	$260.6 \pm 146.1^{ab}{}_{A}$	$290.9 \pm 118.7^{ab}{}_{A}$	**0.030***
P value	0.671	**0.000***	**0.029***	0.127	0.257	0.767	**0.010***	0.306	0.153	0.148	
Bioyield Point (N)											
Day 1	$382.2 \pm 164.9^{d}{}_{B}$	$484.7 \pm 95.8^{bc}{}_{A}$	$503.9 \pm 83.7^{bc}{}_{A}$	$473.2 \pm 86.1^{cd}{}_{A}$	$532.7 \pm 70.5^{abc}{}_{A}$	$536.0 \pm 94.6^{abc}{}_{A}$	$482.7 \pm 100.6^{bc}{}_{A}$	$556.4 \pm 139.0^{abc}{}_{A}$	$574.0 \pm 149.9^{ab}{}_{A}$	$600.5 \pm 137.9^{a}{}_{A}$	**0.000***
Day 5	$543.4 \pm 177.5^{a}{}_{A}$	$553.5 \pm 139.1^{a}{}_{A}$	$523.5 \pm 176.3^{a}{}_{A}$	$512.8 \pm 206.9^{a}{}_{A}$	$521.8 \pm 166.9^{a}{}_{A}$	$528.8 \pm 141.0^{a}{}_{A}$	$470.2 \pm 145.6^{a}{}_{A}$	$515.4 \pm 115.0^{a}{}_{AB}$	$503.4 \pm 112.2^{a}{}_{A}$	$562.6 \pm 110.1^{a}{}_{A}$	0.523
Day 10	$382.0 \pm 193.7^{bc}{}_{B}$	$376.9 \pm 154.8^{bc}{}_{B}$	$499.4 \pm 261.4^{abc}{}_{A}$	$560.4 \pm 286.3^{a}{}_{A}$	$470.1 \pm 283.4^{abc}{}_{A}$	$542.1 \pm 281.8^{ab}{}_{A}$	$359.6 \pm 138.9^{c}{}_{B}$	$437.5 \pm 136.9^{abc}{}_{B}$	$422.5 \pm 112.2^{abc}{}_{B}$	$392.3 \pm 145.8^{abc}{}_{B}$	**0.001***
P value	**0.001***	**0.000***	0.871	0.278	0.415	0.964	**0.001***	**0.003***	**0.000***	**0.000***	

Data expressed as mean ± standard deviation (SD). Letters "a–c" indicate the significant differences ($P < 0.05$) when comparing the coating used within the same row for each day of storage. Letters "A-C" indicate the significant differences ($P < 0.05$) when comparing the storage time for each type of coating within the same column for each parameter (TSS, pH and firmness). *P* value with a bold font and "*" indicates a significant effect of the coating type within each row and storage time within the same column.

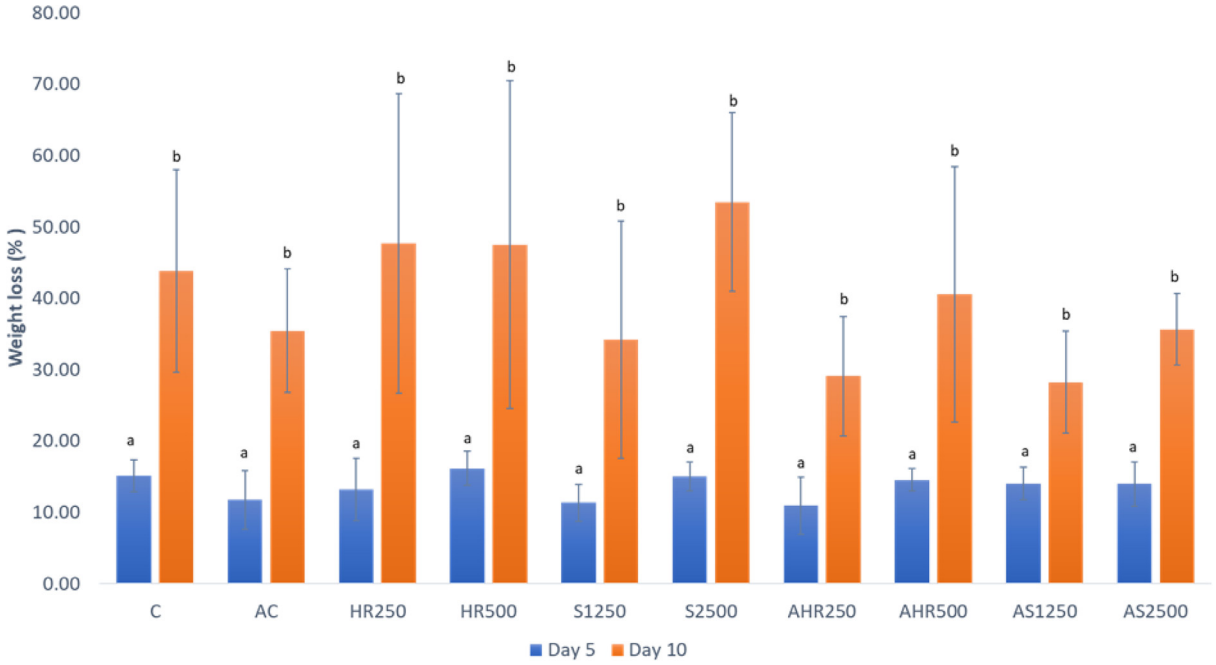

Fig. 1.. Weight loss of avocados during storage, given as a percentage of the original weight. Different letters above error bars (SEM) indicate significant differences ($P < 0.05$).

Workneh, 2020; Maftoonazad & Ramaswamy, 2008). Maftoonazad and Ramaswamy (2008) proposed that the possible influence of weight loss during storage could also contribute to the increase in TSS. In the current study, the increase in the storage time significantly increased the TSS content of samples ($P < 0.05$) except for most alginate-coated samples (i.e., AHR250, AHR500 and AS1250). This was consistent with another study, where sodium alginate coating (with yeast) delayed the increase in TSS and reduced weight loss during storage at 25 °C for 12 days (Iñiguez-Moreno et al., 2021). Saucedo-Pompa et al. (2009) reported similar results with avocados coated with candelilla wax and ellagic acid and stored at a lower temperature (4 °C). The significant increase in the TSS content in the additive-only samples might be due to the significant increase in microbial counts (TVC) during storage, which is obvious from the visual appearance (Fig. 2). High microbial degradation rate in the fruits can increase the solids loss as reported in the literature (Mangaraj et al., 2012). This is also consistent with the Pearson correlation in our study, which showed a significant positive correlation between TVC and TSS (Coefficient = 0.326**).

3.3. pH

During ripening, avocados utilise organic acids for metabolic activities, which causes a decrease in the total acidity and, therefore, increases the pH (Aguirre-Joya et al., 2017; Salameh et al., 2022; Vinha et al., 2013). During storage, control and additive-only samples' pH values increased significantly from day 5 to 10 ($P < 0.05$) (Table 2). The alginate-coated samples showed less variation in pH; they either remained the same or decreased slightly on day 10. All alginate-coated samples showed significantly lower pH values on day 10 than the additive-only counterparts, suggesting that alginate coating delayed biochemical reactions due to ripening. These results were similar to other studies (Iñiguez-Moreno et al., 2021; Maftoonazad & Ramaswamy, 2008; Saucedo-Pompa et al., 2009).

3.4. Firmness and bioyield point

The firmness of avocados decreases as the storage time progresses; this is mainly due to the hydrolysis of cell wall polysaccharides by several enzymes (i.e., pectinase, polygalacturonase and β-galactosidase) (Defilippi et al., 2018; Giuggioli et al., 2021). Nevertheless, in the current study, the firmness values did not differ significantly from day 1 to 10 (Table 2).

Regarding the coating effect, most alginate-coated samples (except AC on day 5) had similar values to their additive-only counterparts. The comparisons between samples C and AC, C and additive-only samples and AC and alginate-coated samples did not reveal any significant difference. Existing literature corroborates that coated avocados tend to maintain their firmness (or lose firmness at a slower rate) since low O_2 and high CO_2 levels yielded by the coating material limit the enzyme activity (Aguirre-Joya et al., 2017; Garcia et al., 2022; Iñiguez-Moreno et al., 2021; Le et al., 2021; Maftoonazad & Ramaswamy, 2005, 2008). Among those, the only study that employed sodium alginate as the primary coating material was that of Iñiguez-Moreno et al. (2021), where the same storage temperature was also used. Still, the alginate concentrations, additional ingredients and RH values in those studies differed from the current study. Although it is tempting to attribute the discrepancy to varying storage conditions (i.e., temperature and RH), coating formulations and the degree of maturity of the fruit, which is not always clearly stated in the studies, further studies need to be conducted to confirm the firmness values obtained in the current study.

The samples' bioyield point (BYP) was also studied to identify a possible relationship between the samples or any correlation with increasing storage time. There is limited data in the existing literature on BYP and avocados (or coatings applied to avocados). Landahl and Terry (2020) reported a decrease in the BYP of uncoated avocados stored at 12 °C for 11 days. Similarly, Valencia et al. (2022) found that the BYP values of uncoated avocados decreased during storage at 27 °C for up to 5 days. The current study revealed a significant decrease in the BYP values of the alginate-coated samples during storage ($P < 0.05$), with values remaining similar from day 1 to 5. The dehydration of the avocado skin accelerates fruit ripening during storage (Lallum et al., 2004). It can be assumed that avocados coated with alginate did not start to dehydrate until after day 5 since the weight loss on day 5 was moderate (Figure 1), followed by a significant increase on day 10 of storage. Like other hydrophilic polysaccharides, alginate has weak mechanical properties and is a poor moisture barrier (Alves et al., 2011).

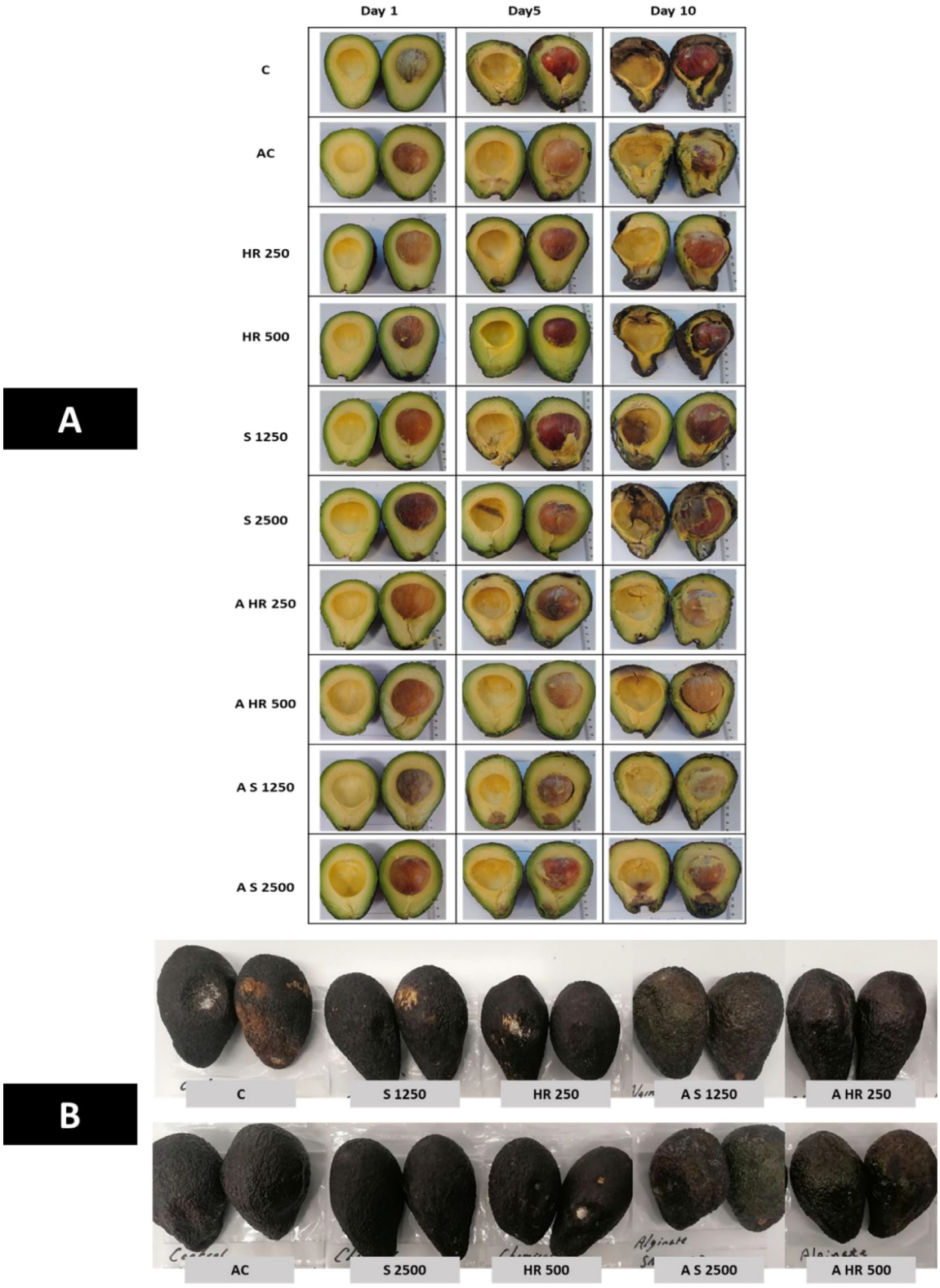

Fig. 2.. Visual internal (A) appearance (during 10 days of storage) and external (B) appearance (after 10 days of storage) of untreated avocado (C), avocado coated with alginate (10 g/L) (AC), avocado samples immersed in 4-Hexylresorcinol (250 and 500 mg/L) and sodium metabisulphite (1250 and 2500 mg/L) solutions without alginate (HR250, HR500, S1250 and S2500) or with 10 g/L alginate (AHR250, AHR500, AS1250 and AS2500).

This might explain the higher moisture loss and loss of firmness on day 10.

Unlike the alginate-coated samples, the additive-only samples retained the BYP values over the storage period. It is unclear why a different trend was observed in the samples treated with additives (i.e., 4-HR or SMBS only). It could be that interaction with the skin and the additives resulted in the desiccation and hardening of the fruit's pericarp. However, this could not be elaborated further due to the scarcity of data on the BYP values of avocados upon storage.

3.5. Appearance

The internal images (flesh) of the avocados can be seen in Fig. 2(a). The deterioration was most evident in the control sample (C) after 10 days of storage, with some darkening and grey patches in the flesh. Le et al. (2021) reported that the internal appearance of the uncoated avocado was grey and almost rotten after 7 days of storage at 23 °C, compared to samples coated with zinc-oxide (ZnO) nanoparticles-added polysaccharide coating. Similarly, in the study of Aguirre-Joya et al. (2017) and Iñiguez-Moreno et al. (2021), discolouration of the flesh was evident in the uncoated avocados at ambient temperatures in comparison to samples coated using a bioactive and biodegradable coating of candelilla wax, pectin, aloe mucilage and purified polyphenols from *Larrea tridentata*. On day 10, the samples with alginate coating with chemical additives had a visual appearance that most resembled the image of the samples on day 1. The samples without the alginate coating and sample AC developed a darker colour and shrivelled appearance at the end of the storage period.

Figure 2(b) shows the images of the skin after 10 days. There was evidence of microbial growth and darkening in the samples without the alginate coating. The latter phenomenon was ascribed to the chlorophyll breakdown by the chlorophyllase enzyme as part of the ripening process (Jimenez et al., 2015). Kassim and Workneh (2020) described the untreated avocados as having a dull/darker exterior and shrivelled appearance with signs of mould development after storage at ambient temperature and RH. In the current study, the alginate-coated samples appeared less dark and free from defects and signs of microbial growth. Likewise, Jimenez et al. (2015) reported a similar protective effect of a coating based on modified cassava starch.

3.6. Colour measurements

3.6.1. Internal (flesh)

As can be seen in Table 3, no significant impact ($P > 0.05$) of the coating was observed at any of the time points. On the other hand, storage resulted in a significant decrease in the L* values after 10 days ($P < 0.05$), indicative of enzymatic browning. For a specific storage period, the alginate-coated samples registered no significant difference in lightness. Those findings were in line with what was obtained in previous studies (Cenobio-Galindo et al., 2019; Garcia et al., 2022; Maftoonazad & Ramaswamy, 2005). Mendoza-Gómez et al. (2017) reported a decrease in the L* values after 3 h of storage at 25 °C and 70% RH when the avocado slices were coated with gellan gum-based coating with the inclusion of 4-HR and other ingredients. The sample maintained the green-yellow pigment (b* value) for 8 h and preserved the visual quality. Due to the much shorter storage time used in that study, further comparisons could not be made.

Gómez-López (2002) reported that sodium sulphite-treated samples (either alone or in combination with citric and ascorbic acid) achieved better retention of L* values of avocado halves during storage at 7 °C for 15 days. López-Ramírez and Duarte-Sierra (2020) stated that the use of SMBS (0.0035%, along with 0.01% ascorbic acid and heat treatment at 60 °C for 3 min) was a significant factor in preserving the L* value of the avocado paste stored at 25 °C (66% RH) for 3 h. This effect was not observed with the control samples and sodium metabisulphite-treated samples (i.e., sample C vs. S1250 and S2500 and sample AC

Table 3
Internal flesh colour of untreated avocado (C), avocado coated with alginate (10 g/L) (AC), avocados immersed in 4-Hexylresorcinol (250 and 500 mg/L) and sodium metabisulphite (1250 and 2500 mg/L) solutions without alginate (HR250, HR500, S1250 and S2500) or with 10 g/L alginate (AHR250, AHR500, AS1250 and AS2500) during 10 days of storage.

Colour value	Number of days in storage	Coating type										*P* Value
		C	AC	HR250	HR500	S1250	S2500	AHR250	AHR500	AS1250	AS2500	
L*	**1**	$79.3 \pm 11.87^{a}{}_{A}$	$77.31 \pm 9.60^{a}{}_{A}$	$78.80 \pm 9.31^{a}{}_{A}$	$78.50 \pm 8.15^{a}{}_{A}$	$78.26 \pm 9.38^{a}{}_{A}$	$78.68 \pm 9.77^{a}{}_{A}$	$79.49 \pm 11.61^{a}{}_{A}$	$79.94 \pm 10.96^{a}{}_{A}$	$78.64 \pm 11.75^{a}{}_{A}$	$78.42 \pm 9.44^{a}{}_{A}$	0.999
	5	$73.61 \pm 8.32^{a}{}_{AB}$	$76.05 \pm 10.67^{a}{}_{A}$	$75.72 \pm 6.61^{a}{}_{A}$	$73.37 \pm 6.01^{a}{}_{B}$	$73.92 \pm 8.72^{ab}{}_{A}$	$73.02 \pm 11.41^{a}{}_{AB}$	$73.28 \pm 9.35^{a}{}_{B}$	$72.76 \pm 10.08^{a}{}_{A}$	$73.54 \pm 11.53^{a}{}_{AB}$	$72.03 \pm 10.97^{a}{}_{B}$	**0.747**
	10	$67.62 \pm 2.36^{a}{}_{B}$	$66.78 \pm 7.09^{a}{}_{B}$	$70.89 \pm 4.66^{a}{}_{B}$	$69.18 \pm 3.56^{a}{}_{B}$	$65.22 \pm 2.47^{a}{}_{B}$	$68.23 \pm 0.65^{a}{}_{B}$	$69.97 \pm 9.22^{a}{}_{B}$	$63.64 \pm 9.54^{a}{}_{A}$	$68.95 \pm 13.92^{a}{}_{B}$	$68.97 \pm 10.08^{a}{}_{B}$	0.483
	P Value	**0.000***	**0.000***	**0.000***	**0.000***	**0.000***	**0.000***	**0.000***	0.426	**0.003***	**0.001***	
a*	**1**	$-1.28 \pm 0.83^{a}{}_{B}$	$-1.25 \pm 1.20^{a}{}_{B}$	$-2.97 \pm 1.87^{ab}{}_{B}$	$-2.53 \pm 1.36^{ab}{}_{B}$	$-2.35 \pm 0.07^{ab}{}_{B}$	$-2.88 \pm 0.86^{ab}{}_{B}$	$-1.63 \pm 0.04^{a}{}_{A}$	$-2.00 \pm 1.83^{a}{}_{B}$	$-3.28 \pm 2.13^{ab}{}_{C}$	$-4.73 \pm 1.93^{b}{}_{C}$	**0.000***
	5	$-1.20 \pm 1.83^{ab}{}_{B}$	$0.17 \pm 0.52^{a}{}_{B}$	$-1.43 \pm 2.32^{ab}{}_{B}$	$-2.51 \pm 2.16^{ab}{}_{B}$	$-0.94 \pm 0.44^{ab}{}_{B}$	$-3.55 \pm 0.40b_{B}$	$-0.34 \pm 1.20^{a}{}_{A}$	$-0.52 \pm 1.68^{a}{}_{B}$	$0.07 \pm 1.68^{a}{}_{B}$	$-0.63 \pm 0.09^{ab}{}_{B}$	**0.001***
	10	$2.32 \pm 1.92^{a}{}_{A}$	$3.53 \pm 0.37^{a}{}_{A}$	$2.69 \pm 2.83^{a}{}_{A}$	$1.64 \pm 1.20^{a}{}_{A}$	$3.23 \pm 3.44^{a}{}_{A}$	$2.87 \pm 2.44^{a}{}_{A}$	$2.73 \pm 0.33^{a}{}_{A}$	$6.11 \pm 1.12^{a}{}_{A}$	$2.98 \pm 1.53^{a}{}_{A}$	$3.90 \pm 2.55^{a}{}_{A}$	0.373
	P Value	**0.000***	**0.000***	**0.000***	**0.000***	**0.000***	**0.000***	0.071	**0.000***	**0.000***	**0.000***	
b*	**1**	$35.15 \pm 4.15^{a}{}_{A}$	$35.21 \pm 3.50^{a}{}_{A}$	$36.88 \pm 6.52^{a}{}_{A}$	$35.70 \pm 5.05^{a}{}_{A}$	$35.43 \pm 2.63^{a}{}_{A}$	$34.11 \pm 2.24^{a}{}_{A}$	$34.76 \pm 4.01^{a}{}_{A}$	$34.38 \pm 4.63^{a}{}_{A}$	$34.58 \pm 3.98^{a}{}_{A}$	$36.07 \pm 3.84^{a}{}_{A}$	0.187
	5	$34.59 \pm 6.37^{a}{}_{A}$	$34.97 \pm 6.68^{a}{}_{AB}$	$36.43 \pm 8.29^{a}{}_{AB}$	$34.24 \pm 5.02^{a}{}_{A}$	$34.92 \pm 6.47^{a}{}_{AB}$	$33.69 \pm 5.37^{a}{}_{A}$	$34.75 \pm 3.31^{a}{}_{A}$	$34.46 \pm 0.47^{a}{}_{A}$	$35.65 \pm 1.19^{a}{}_{A}$	$33.33 \pm 3.48^{a}{}_{AB}$	0.716
	10	$32.34 \pm 5.03^{a}{}_{A}$	$31.47 \pm 8.24^{a}{}_{B}$	$32.78 \pm 2.42^{a}{}_{B}$	$34.02 \pm 6.04^{a}{}_{A}$	$30.76 \pm 2.35^{a}{}_{B}$	$30.29 \pm 0.55^{a}{}_{A}$	$33.83 \pm 6.31^{a}{}_{A}$	$28.33 \pm 9.56^{a}{}_{B}$	$32.10 \pm 11.44^{a}{}_{A}$	$31.76 \pm 4.56^{a}{}_{B}$	0.413
	P Value	0.446	**0.027***	**0.024***	0.630	**0.018***	0.083	0.716	**0.004***	0.140	**0.023***	

Data expressed as mean ± standard deviation (SD). Letters "a–c" indicate the significant differences ($P < 0.05$) when comparing the coating used within the same row for each day of storage. Letters "A-C" indicate the significant differences ($P < 0.05$) when comparing the storage time for each type of coating within the same column for each parameter (L*, a*, b*). *P* value with a bold font and "*" indicates a significant effect of the coating type within each row and storage time within the same column.

vs. AS1250 and AS2500) in the current study. It seems that the direct contact between SMBS and the packed food is crucial for SMBS to pose its anti-browning/antioxidant effect. In the two abovementioned studies, sulphite was applied directly to the flesh of the avocado (i.e., avocado paste or cut halves). This may explain the ineffectiveness of SMBS in the present study, when applied to the avocado skin, to penetrate through the skin and act as an anti-browning agent or antioxidant. The fact that samples containing sulphites and coated with alginate, compared to additive-only samples, had a better shiny appearance may indicate that the alginate had more impact on colour than SMBS.

The ability of the bioactive antioxidant molecule to penetrate or permeate across the fruit skin/peel and its amount within the flesh or the remaining amount in the coating may determine if the biomolecule penetrated the peel or was restrained by the coating. In a recent study, Tampucci et al. (2021) tested the diffusion ability of tyrosol (a hydrophilic antioxidant) by quantification in intact fruit, peel and flesh during 7 days of storage. The authors reported the ability of tyrosol to permeate across the fruit peel, which was confirmed by a decreased content in the peel and an increase in the flesh. Thus, future work may need to compare the concentration of 4-HR and SMBS molecules in these three regions to gain a better understanding of the migration kinetics of the active molecules during storage.

The a* values were slightly different between the different sample varieties on days 1 and 5; however, on day 10, all samples had similar values. The a* values changed from more negative values to positive during storage ($P < 0.05$). There was a decrease in the b* values; this effect was seen more prominently on day 10 in half of the samples, but not explicitly pertaining to additive-only or alginate-coated versions. The changes in the a* and b* values indicated that the flesh became less green and less yellow, respectively. Those results were consistent with other studies (Garcia et al., 2022; Maftoonazad & Ramaswamy, 2005).

An interesting finding with L* and a* values was that the samples treated with 4-HR as an additive-only treatment showed colour deterioration. However, more constant colour parameters and colour stability were observed when alginate was added to 4-HR. Similar results were obtained in a previous study (Perez-Gago et al., 2006), where 4-HR was slightly better at preserving the colour of fresh-cut apples by reducing browning compared to uncoated apples. However, its effectiveness was somewhat higher when incorporated into whey protein concentrate (WPC) as a coating formulation, probably due to the antioxidant effect of WPC. The authors also reported that browning was faster when the samples remained coated with 4-HR than in the control. The lack of antioxidant effect in samples covered with 4-HR suggests its use combined with biopolymers or other antioxidants. It also shows the antioxidant function of alginate in the formulation. 4-HR was reported to be more effective when combined with ascorbic acid on apple slices of several cultivars than when each antioxidant was used alone (Luo & Barbosa-Cánovas, 2016). In another study, 4-HR alone could not inhibit surface browning in pears but suppressed core browning. However, when combined with sodium erythorbate, less browning of cut surfaces, skin edges, and core of pears was observed than with sodium erythorbate (Sapers & Miller, 1998).

3.6.2. External (skin)

The skin of *Hass* avocados changes colour from green to purple/black during storage due to the chlorophyll degradation and synthesis of pigments such as cyanidin 3-O-glucosidase (Giuggioli et al., 2021; Kassim & Workneh, 2020; Zafar & Sidhu, 2018). As a result, avocado skin loses brightness registering lower L* values over time (Cenobio-Galindo et al., 2019; Saucedo-Pompa et al., 2009; Sierra et al., 2019). In the current study, storing the samples for 10 days resulted in no change in the L* values of most alginate-coated samples (Table 4). This supports the findings that the application of coatings facilitates better retention of lightness during storage (Aguirre-Joya et al., 2017; Kassim & Workneh, 2020; Le et al., 2021; Maftoonazad & Ramaswamy, 2005, 2008). However, an increase in the L* values was observed with the other samples after 10

Table 4
External skin colour of untreated avocado (C), avocado coated with alginate (10 g/L) (AC), avocados immersed in 4-Hexylresorcinol (250 and 500 mg/L) and sodium metabisulphite (1250 and 2500 mg/L) solutions without alginate (HR250, HR500, S1250 and S2500) or with 10 g/L alginate (AHR250, AHR500, AS1250 and AS2500) during 10 days of storage.

Colour value	Number of days in storage	Coating type										*P* Value
		C	AC	HR250	HR500	S1250	S2500	AHR250	AHR500	AS1250	AS2500	
L*	**1**	$36.89 \pm 10.47^{a}{}_{B}$	$36.70 \pm 5.08^{a}{}_{B}$	$36.50 \pm 6.64^{a}{}_{A}$	$35.92 \pm 10.28^{a}{}_{B}$	$37.89 \pm 9.47^{a}{}_{A}$	$35.32 \pm 7.45^{a}{}_{B}$	$36.71 \pm 3.51^{a}{}_{A}$	$36.63 \pm 5.32^{a}{}_{B}$	$35.84 \pm 7.56^{a}{}_{B}$	$35.43 \pm 4.19^{a}{}_{B}$	0.716
	5	$36.38 \pm 6.10^{aA}{}_{B}$	$39.31 \pm 7.47^{a}{}_{AB}$	$36.04 \pm 5.83^{a}{}_{A}$	$36.11 \pm 5.91^{aA}{}_{B}$	$36.46 \pm 6.69^{a}{}_{A}$	$35.87 \pm 6.12^{a}{}_{B}$	$37.25 \pm 6.29^{a}{}_{A}$	$39.97 \pm 5.97^{a}{}_{A}$	$39.72 \pm 8.58^{a}{}_{A}$	$38.18 \pm 6.81^{a}{}_{A}$	0.066
	10	$39.53 \pm 3.90^{ab}{}_{A}$	$40.05 \pm 3.46^{a}{}_{A}$	$38.81 \pm 3.79^{ab}{}_{A}$	$39.57 \pm 4.28^{ab}{}_{A}$	$40.44 \pm 5.87^{a}{}_{A}$	$39.52 \pm 4.91^{ab}{}_{A}$	$36.45 \pm 1.20^{b}{}_{A}$	$38.33 \pm 0.26^{ab}{}_{AB}$	$37.28 \pm 0.83^{ab}{}_{AB}$	$39.71 \pm 1.39^{ab}{}_{A}$	**0.005***
	P Value	**0.012***	**0.010***	0.064	**0.023***	0.060	**0.002***	0.692	**0.008***	**0.016***	**0.000***	
a*	**1**	$3.38 \pm 0.97^{a}{}_{C}$	$4.65 \pm 0.58^{ab}{}_{B}$	$5.19 \pm 1.64^{a}{}_{AB}$	$4.11 \pm 0.21^{ab}{}_{C}$	$4.58 \pm 0.49^{ab}{}_{B}$	$5.24 \pm 0.76^{a}{}_{B}$	$4.19 \pm 0.68^{ab}{}_{B}$	$5.10 \pm 0.58^{a}{}_{A}$	$4.12 \pm 1.02^{ab}{}_{A}$	$4.49 \pm 0.14^{ab}{}_{AB}$	**0.003***
	5	$4.48 \pm 0.73^{ab}{}_{B}$	$3.70 \pm 0.43^{b}{}_{A}$	$4.39 \pm 0.01^{ab}{}_{B}$	$4.86 \pm 0.04^{a}{}_{B}$	$4.80 \pm 0.00^{a}{}_{B}$	$5.19 \pm 0.85^{a}{}_{B}$	$4.64 \pm 0.36^{a}{}_{AB}$	$3.71 \pm 0.15^{b}{}_{B}$	$4.46 \pm 0.61^{ab}{}_{A}$	$4.41 \pm 0.54^{ab}{}_{B}$	**0.000***
	10	$5.58 \pm 0.01^{ab}{}_{A}$	$5.69 \pm 0.56^{ab}{}_{C}$	$5.82 \pm 0.11^{ab}{}_{A}$	$5.75 \pm 0.20^{ab}{}_{A}$	$5.86 \pm 0.48^{ab}{}_{A}$	$6.16 \pm 0.89^{a}{}_{A}$	$5.22 \pm 1.8^{ab}{}_{A}$	$5.44 \pm 1.48^{ab}{}_{A}$	$5.08 \pm 0.82^{b}{}_{A}$	$5.19 \pm 0.41^{ab}{}_{A}$	**0.029***
	P Value	**0.000***	**0.000***	**0.008***	**0.000***	**0.000***	**0.029***	**0.020***	**0.000***	0.108	**0.017***	
b*	**1**	$0.60 \pm 0.61^{a}{}_{A}$	$-0.59 \pm 0.39^{a}{}_{A}$	$0.10 \pm 3.12^{a}{}_{A}$	$-0.53 \pm 0.37^{a}{}_{A}$	$0.48 \pm 1.10^{a}{}_{A}$	$-0.65 \pm 2.54^{a}{}_{A}$	$0.03 \pm 0.33^{a}{}_{A}$	$-0.50 \pm 0.00^{a}{}_{AB}$	$-0.58 \pm 1.09^{a}{}_{A}$	$0.78 \pm 1.85^{a}{}_{A}$	0.456
	5	$-3.83 \pm 1.21^{b}{}_{B}$	$-0.95 \pm 0.49^{aA}{}_{AB}$	$-3.74 \pm 0.93^{b}{}_{B}$	$-3.75 \pm 1.87^{b}{}_{C}$	$-3.45 \pm 0.77^{b}{}_{C}$	$-3.72 \pm 0.66^{b}{}_{B}$	$-2.58 \pm 0.44^{b}{}_{B}$	$0.27 \pm 0.15^{a}{}_{A}$	$-0.33 \pm 1.17^{a}{}_{A}$	$-0.60 \pm 0.15^{a}{}_{A}$	**0.000***
	10	$-1.62 \pm 2.31^{a}{}_{A}$	$-1.73 \pm 0.05^{a}{}_{B}$	$-0.74 \pm 3.59^{a}{}_{A}$	$-2.12 \pm 1.35^{a}{}_{B}$	$-1.57 \pm 2.93^{a}{}_{B}$	$-1.69 \pm 2.53^{a}{}_{A}$	$-2.13 \pm 0.09^{a}{}_{B}$	$-1.26 \pm 1.88^{a}{}_{B}$	$-1.27 \pm 0.03^{a}{}_{A}$	$-0.15 \pm 0.15^{a}{}_{A}$	0.111
	P Value	**0.000***	**0.009***	**0.000***	**0.000***	**0.000***	**0.000***	**0.000***	**0.043***	0.191	0.434	

Data expressed as mean ± standard deviation (SD). Letters "a–c" indicate the significant differences ($P < 0.05$) when comparing the coating used within the same row for each day of storage. Letters "A–C" indicate the significant differences ($P < 0.05$) when comparing the storage time for each type of coating within the same column for each parameter (L*, a*, b*). *P* value with a bold font and "*" indicates a significant effect of the coating type within each row and storage time within the same column.

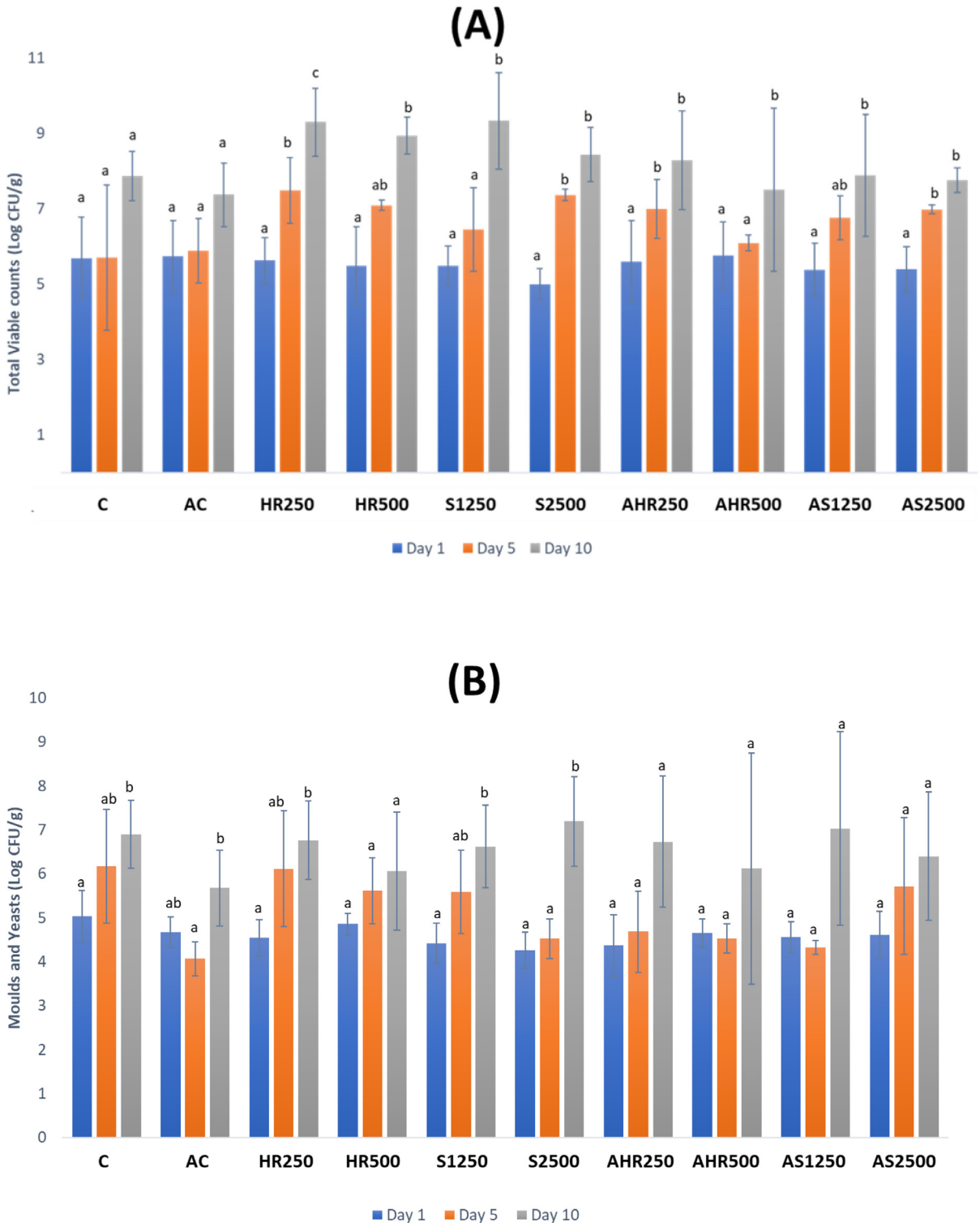

Fig. 3. Total viable counts (A) and mould & yeasts counts (B) (Log CFU/g) during 10 days of storage of untreated avocado (C), coated avocado with alginate films (10 g/L) (AC), avocado samples immersed in 4-Hexylresorcinol (250 and 500 mg/L) and sodium metabisulphite (1250 and 2500 mg/L) solutions without alginate (HR250, HR500, S1250 and S2500) or with 10 g/L alginate (AHR250, AHR500, AS1250 and AS2500). Different letters above error bars (SEM) indicate significant differences ($P < 0.05$).

days. The reason why an opposite trend was observed with some samples in the current study was unclear.

The L^* values of the additive-only samples were not different from the alginate-coated counterparts for any storage duration. Similarly, Cenobio-Galindo et al. (2019) reported no significant differences in the L^* values between different treatments (differing concentrations of nano-emulsion made of orange essential oil and stored at 6°C for up to 60 days).

The effect of storage on a^* and b^* values was significant; increased storage time (10 days) increased the a^* values (less green, more red)

Table 5
Pearson correlation coefficients.

		Effect of time	C* Internal	C* External	pH	Total soluble solids	Firmness	Bioyield point	Total viable counts	Moulds and yeasts
Effect of time	Pearson correlation	–	–	0.239**	0.130**	0.331**	0.000	−0.160**	0.721**	0.489**
	Sig. (2-tailed)		0.000	0.000	0.000	0.000	0.910	0.000	0.000	0.000
Chroma internal	Pearson correlation		–	−0.020	−0.030	–	−0.150**	−.0193**	−0.100	−0.130
	Sig. (2-tailed)			0.630	0.540	0.000	0.000	0.000	0.270	0.190
Chroma external	Pearson correlation			–	0.070	0.159**	0.060	0.016	0.444**	0.349**
	Sig. (2-tailed)				0.110	0.000	0.100	0.635	0.000	0.000
pH	Pearson correlation				–	0.384**	0.070	0.152**	−0.080	0.020
	Sig. (2-tailed)					0.000	0.110	0.000	0.370	0.860
Total soluble solids	Pearson correlation					–	−0.020	0.054	0.326**	0.120
	Sig. (2-tailed)						0.650	0.214	0.000	0.220
Firmness	Pearson correlation						–	0.679**	−0.090	0.060
	Sig. (2-tailed)							0.000	0.360	0.540
Bioyield point	Pearson correlation							–		
	Sig. (2-tailed)									
Total viable counts	Pearson correlation							0.007	–	0.651**
	Sig. (2-tailed)							0.938		0.000
Moulds and yeasts	Pearson correlation							0.023		–
	Sig. (2-tailed)							0.814		

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

and decreased the b* values (less yellow, more blue). These results agreed with other studies (Garcia et al., 2022; Maftoonazad & Ramaswamy, 2008; Sierra et al., 2019).

Alginate-coated samples (except AHR500) had higher b* values when compared to additive-only counterparts on day 5. A similar trend was observed in another study (Maftoonazad & Ramaswamy, 2005), where coated avocados had higher b* values than the uncoated samples when stored for up to 6 days at 20°C.

3.7. Microbial count

TVC increased in most samples during storage ($P < 0.05$) (Fig. 3). The alginate-coated samples had a lower but insignificant increase in TVC on day 10 compared to the additive-only counterparts. Yeast and mould count increased in all samples from day 1 to 10. However, neither this increase nor the differences between the additive-only and alginate-coated samples were significant. Coatings can aid in lowering microbial contamination since they form physical barriers between the produce and its immediate environment (Garcia & Davidov-Pardo, 2021b). The results obtained in the current study implied that additive-only and alginate-coated samples did not differ in how they promoted microbial growth. Aguiló-Aguayo et al. (2014) reported a lower yeast and mould count in non-treated fresh-cut avocados stored at 4 °C for up to 15 days; this difference is an expected implication of the lower incubation temperature used in that study. Reducing the rate of microbial growth and fungal decay by incorporating antimicrobial compounds into packaging materials (including alginate) is successfully applied to avocados and other produce (Fu et al., 2022; Iñiguez-Moreno et al., 2020, 2021; Munhuweyi et al., 2020; Parreidt et al., 2018), but this was not within the scope of this study.

3.8. Correlations between the parameters studied

Storage time correlated with internal and external chroma, pH, TSS, BYP, TVC and MYC ($P < 0.05$) (Table 5). There was a fairly high positive correlation between the storage time and microbial counts, with TVC and MYC having correlation coefficients of $r = 0.721$ and 0.489, respectively ($P < 0.01$). All parameters, apart from internal chroma, were positively correlated with time.

With regards to correlations between the parameters studied, the present work showed that the pH positively and moderately correlated with TSS, as was found in another study (Cenobio-Galindo et al., 2019), where TSS values related to the pH values of avocados stored at 6 °C for up to 60 days. TVC correlated positively and strongly ($P < 0.01$) with MYC. This was similar to the findings of Tan et al. (2020), which were observed with frozen durian fruit stored for one year.

Cho et al. (2021) reported strong correlations between the external colour features (L*, a* and b*) and firmness values, with r values ranging from −0.69 to −0.83 during the ripening process when unripe *Hass* avocados were kept at 10 °C and 95% RH. Such a correlation was not observed in the current study, possibly because of the fruits' different maturity (i.e., unripe vs. ready-to-eat).

4. Conclusion

This study aimed at producing an alginate-based active edible packaging with antioxidant potential using 4-hexylresorcinol (4-HR) and sodium metabisulphite (SMBS) to extend the shelf life of *Hass* avocados. Alginate-coated samples prevented weight loss and darkening during storage. The samples without alginate or with alginate only and no chemicals, developed a darker colour and shrivelled appearance at the end of the storage. 4-HR was shown to protect the colour only when incorporated into the alginate coatings. Additive-only and alginate-coated samples did not differ in how they promoted microbial growth; the length of the storage time was a determining factor for microbial quality. Future work may include determining the antioxidant power of the formulations, detecting the residue of 4-HR and SMBS in the avocado flesh to ensure the safety of the produce, and investigating the possible synergistic effect of 4-HR and SMBS or 4-HR combined with other coating materials on avocado quality.

Ethical statement - studies in humans and animals AFR

This work did not use humans and/or animals.

Declaration of Competing Interest

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

CRediT authorship contribution statement

E. Hebishy: Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Writing – review & editing. **A.A.**

Tas: Formal analysis, Investigation, Writing – original draft, Writing – review & editing.

Data availability

Data will be made available on request.

Acknowledgements

We thank Oliver Horne and Sophie Bowers for their assistance in conducting experimental work. We are grateful to Greencell Ltd for providing the avocados and Xyrex Ltd for providing 4-HR.

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