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Gum Arabic edible coating embedded aqueous plant extracts: Interactive effects of partaking components and its effectiveness on cold storage of fresh-cut capsicum

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ABSTRACT

This study investigated the interactive effects of components in gum Arabic-based coating enriched with aqueous extracts of *Syzygium aqueum*, *Diploglottis bracteata*, and *Tasmannia lanceolata* on properties of edible coating/film. Response surface methodology was employed to optimize the films based on their physical and permeability properties. It was shown that the concentration of the components significantly influenced these characteristics. The coating demonstrated strong antimicrobial activity against *Pseudomonas viridiflava*, a main cause of soft rot in vegetables, when using 5.00% *S. aqueum*, 5.00% *D. bracteata*, and 9.35% *T. lanceolata* with lower concentrations of gum Arabic and MCT oil. The optimized coating was applied to fresh-cut red capsicum, and its effects were evaluated. The coating effectively inhibited microbial growth, maintaining low bacterial load (ca. 3 log CFU. g^{-1}) until day 10 of storage. Sensory evaluations also showed positive liking scores for appearance, aroma, and flavor, indicating that the coating enhanced the overall sensory experience of the capsicum. Despite these positive outcomes, challenges regarding moisture retention and firmness preservation during storage were identified. The coating did not adequately preserve these qualities, highlighting the need for further research to optimize the formulation for commercial applications. Nonetheless, incorporating plant extracts in the gum Arabic-based coating holds promise for extending the shelf life of fresh-cut capsicum while improving its sensory attributes.

1. Introduction

Minimal processed foods such as fresh-cut fruits and vegetables have been gaining interests among consumers, which are associated with freshness, nutrition, and convenience for today's hectic lifestyle. Bell pepper (*Capsicum annuum* L.), also known as capsicum, is among the top ten most popular vegetables worldwide (Sowder, 2021) that is rich in health promoting bioactive compounds such as carotenoids including pro-vitamin A active carotenoids, polyphenolic compounds, and vitamin C (Murcia et al., 2009). The health beneficial attributes of capsicum can be a driving contributor to growing its popularity in the fresh-cut produce industry to be either used as a healthy snack or a cooking ingredient. However, the contribution of fresh-cut capsicum to the ready-to-eat food industry is limited due to its high perishability, which results in a short shelf life of 5–7 days (Chen et al., 2018). This is because of physical damages caused by the minimal processing operations such as cutting, slicing, and shredding, which makes them more prone to microbial contamination as well as chemical and enzymatic degradation (Rybak et al., 2020).

The microbial safety of these products has been considered as a pivotal priority for agri-food and public health authorities due to its raw consumption (WHO, 2010) and the vulnerability to food-borne disease outbreaks leading to health and economic burden. For instance, fresh-cut vegetables are susceptible to bacterial soft rot during

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refrigerated storage (Gil & Tudela, 2020) that is mostly caused by ubiquitous fluorescent Pseudomonads (Lee et al., 2013). The pectinolytic and multi-host pathogens, namely *Pseudomonas viridiflava* and *P. fluorescens*, are the main causes of about 40% of spoilage in a wide range of whole and fresh-cut fruits and vegetables worldwide (Liu et al., 2021) including melon, radish, carrot, onion, potato, eggplant, cucumber, artichoke, tomato, and capsicum.

In minimal processing, chlorine-based solutions are conventionally used to disinfect the fruits and vegetables, which is inexpensive with limited efficacy in microbial reduction. Nevertheless, the chlorine residuals can undergo a series of reactions with the organic molecules present in cut surfaces of fruits/vegetables and produce harmful mutagenic and carcinogenic by-products that can pose a risk of toxicity to consumer health (Meireles et al., 2016). Thermal treatments, on the other hand, cannot be applied on fresh-cut fruits and vegetables due to the nature of these products that are mainly aimed for fresh consumption. This leads to an increased interest of manufacturers in non-thermal disinfection methods. Therefore, several studies have investigated the efficacy of non-thermal techniques such as modified atmosphere packaging (Ranjitha et al., 2015), electrolyzed water (Saravanakumar et al., 2021), ozone (Alexopoulos et al., 2013), ultraviolet-C (Rodoni et al., 2012), and pulsed light treatment (Rybak et al., 2021). However, manufacturers still face challenges in not only the antimicrobial effect of these treatments and controlling the growth of pathogenic microorganisms on the nutrient-rich surfaces of fresh-cut produce during their shelf life, but also the considerable investment cost.

There has been an increasing interest in the use of edible coatings as a green and sustainable preservation approach to preserve fruits and vegetables. This involves using biopolymers derived from natural resources as carriers for natural antimicrobials. The edible coating creates a physical barrier on the surface of the produce, which delays moisture loss, respiration, enzymatic reactions and microbial growth by controlled release of bioactive compounds (Yousuf et al., 2018). Polysaccharides are widely used as film-forming agents due to their availability, low cost, hydrophilicity, and gas barrier properties (de Barros Fernandes et al., 2014). Gum Arabic, a hydrophilic and anionic heteropolysaccharide isolated from *Acacia senegal* tree (de Barros Fernandes et al., 2014), has demonstrated preservative efficacy when combined with plant extracts such as tulsi (*Osmium sanctum*) (Murmu & Mishra, 2017), African baobab (*Adansonia digitata*) pulp (Tahir et al., 2020) and roselle (*Hibiscus sabdariffa*) (Yang et al., 2019). Plant extracts are being extensively evaluated as alternatives to chemical preservatives, and their antimicrobial activity is attributed to their organic acid and phenolic components (Yang et al., 2019). Native Australian plants such as *Syzygium aqueum*, *Diploglottis bracteata*, and *Tasmannia lanceolata* are rich in bioactive compounds and have potential antimicrobial properties against microorganisms responsible for capsicum spoilage (Seididamyeh et al., 2023). However, incorporating these plant extracts into edible coatings for preserving fresh-cut fruits and vegetables has not been studied. Thus, this study aimed to optimize an antimicrobial edible coating formulation based on gum Arabic and optimized blends of plant extract from our previous study (Seididamyeh et al., 2023) through response surface methodology, and apply it to fresh-cut red capsicums stored under cold storage for 16 days.

2. Material and methods

2.1. Edible coating preparation

Gum Arabic (Acrōs Organics, UK) solutions at different concentrations (10, 20 and 30%, w/v) were prepared in ultrapure water at 40 °C with magnetic stirring (Industrial Equipment & Control, Thornbury, VIC, Australia). After overnight hydration and dissolution at 4 °C, the extract blends were added dropwise into the solution (1:1 ratio, v/v). Two optimized extract blends, blend 1 (5.28% *S. aqueum* and 4.72% *T. lanceolata*) and blend 2 (5.00% *S. aqueum*, 5.00% *D. bracteata*, and 9.35% *T. lanceolata*), were used based on a previous study (Seididamyeh et al., 2023). Plasticizer was not used in the coating formulation due to the inherent plasticizer-like behavior of the extract blends. Therefore, gum Arabic acted as an anti-plasticizer to aid in coating drying. The mixture was homogenized, sonicated (1 min, 30% amplitude; Sonifier 550 SFX, Branson, Mexico), and degassed under vacuum to remove air bubbles. If necessary (Table 1), medium-chain triglyceride (MCT; Melróse, Mt Waverley, VIC, Australia) oil was added to the gum Arabic solution at 40 °C under magnetic stirring (before adding extract). MCT oil served as a hydrophobic agent to assess its impact on water vapor permeability. This was hypothesized according to literature where hydrophobic agents such as rosehip oil (Paladines et al., 2014) and sunflower oil (Zhang et al., 2016) were added to the edible coatings in order to enhance the barrier properties of edible coating by lowering the water vapor permeability and in turn to avoid the fruit weight loss. Control coating solutions were also prepared without extract blends for comparative purposes.

2.2. Film preparation

The edible films were prepared by casting method, wherein 5 ml of coating solution was evenly spread onto the Teflon-coated plates (5 cm in diameter). Films were then dried at 40 ± 2 °C in a hot air oven (BS300, Sanyo Gallenkamp, Loughborough, UK) for 24 h. The prepared films were peeled off and conditioned at 25 °C and 50% relative humidity in a desiccator containing $Mg(NO_3)_2$ saturated solution (Sigma-Aldrich, St Louis, MO, USA) for 48 h prior to further experiments. This process was done in five replicates to ensure consistency.

2.3. Edible film properties

2.3.1. Film thickness and opacity

A digital caliper (±0.01 mm, Craftright, China) was used to measure the conditioned film thickness. The average of measurements at four random positions for three replications of each film were calculated in mm. Film opacity was determined using a UV–Vis spectrophotometer (Genesys 20, Thermo Fisher Scientific, Waltham, MA, USA) with an empty cuvette as reference (Park et al., 2004), where absorbance at 600 nm was divided by film thickness (mm).

2.3.2. Water vapor permeability

Water vapor permeability (WVP) was measured according to the ASTM E96-95 gravimetric method (ASTM, 2013) with some modification (Sun et al., 2017). The film discs with the diameter of 5 cm were placed on water vapor permeability cups (15 cm^3; 5100 Payne cup, Elecometer, Manchester, UK) containing 4 g of anhydrous silica gel beads (0% RH). After weighing, the cups were placed in a desiccator containing ultrapure water (100% RH) and kept in a 25 °C incubator (TLMRI 250-1-SD, Thermoline Scientific, Wetherill Park, NSW, Australia). The cups were weighed every 4 h during a 24-h period (±0.0001 g). The WVP was calculated using the following equations:

$$WVTR = \frac{\Delta W}{\Delta t \times A} \quad (1)$$

$$WVP = \frac{WVTR \times X}{\Delta \rho} \quad (2)$$

where WVTR is water vapor transmission rate through the film ($g.s^{-1}.m^{-2}$), ΔW is the weight gain (g), Δt is the time of incubation (permeation) (s), A is the permeation area of the film (m^2), WVP is the water vapor permeability ($g.s^{-1}.m^{-1}.Pa^{-1}$), X is the film thickness (m), and Δρ is the water vapor partial pressure difference across the two sides of the film (Pa).

2.3.3. Moisture content and water solubility

Films were cut into square specimens (2 cm × 2 cm) and weighed

Table 1
I-optimal design and the correspondent responses in optimization of antimicrobial properties of edible coating.

Run	Independent Variables			Dependent Variables												
	GA (%)	MCT (%)	Extract Blend	Opacity	WVP (× 10^{-7})	MC	WS	IC_{50}	TPC	Inhibition Zone (mm/10 mg of edible film)				Inhibition Zone (mm/100 µl of edible coating solution)			
										PV	BS	RD	AA	PV	BS	RD	AA
1	10	0.25	2	3	7.01	17.55	51.99	32.87	55.04	6.77	5.36	3.00	3.14	16.33	15.12	19.07	5.72
2	15	0.25	2	3	6.11	15.06	48.57	37.26	45.25	6.77	5.48	2.96	4.28	16.04	13.97	20.61	5.03
3	5	0.50	1	5	4.12	15.63	53.03	31.23	49.52	7.16	6.53	3.98	5.15	14.62	12.78	17.71	3.04
4	15	0.50	1	4	4.39	13.57	44.90	42.65	36.30	6.69	5.53	4.26	6.62	14.50	12.66	16.53	0.00
5	10	0.00	2	2	6.38	17.45	53.25	40.90	49.52	5.74	4.32	2.81	3.27	16.17	15.02	20.55	4.68
6	10	0.25	2	2	5.99	16.68	53.73	32.97	50.46	7.89	4.91	3.21	3.56	16.75	14.43	20.83	4.82
7	5	0.25	2	4	5.77	18.87	65.27	30.76	56.79	7.55	5.32	3.11	3.25	17.47	15.69	21.34	5.60
8	10	0.00	1	3	4.23	14.75	59.76	37.32	41.34	10.44	7.82	4.01	5.69	12.92	12.39	18.37	2.58
9	10	0.25	2	3	5.88	18.36	52.99	30.66	49.84	6.92	4.96	2.88	3.76	16.62	14.21	20.09	5.48
10	5	0.00	1	4	4.41	19.72	80.52	29.32	49.67	10.61	8.03	5.22	5.30	14.51	13.36	19.60	2.94
11	5	0.25	1	4	3.87	15.70	57.48	29.67	48.73	9.38	7.53	4.09	5.07	15.48	12.97	17.50	2.93
12	15	0.00	1	2	3.44	14.59	51.52	40.63	36.69	9.52	7.76	3.67	5.13	15.23	13.23	18.24	4.63
13	10	0.25	1	4	5.15	14.44	59.45	34.99	43.91	7.92	6.33	4.72	4.07	14.36	12.77	18.22	3.83
14	5	0.50	2	5	7.12	18.92	64.64	26.36	63.46	7.84	5.85	4.04	3.63	17.23	14.15	19.28	5.16
15	15	0.50	2	3	9.75	15.93	49.39	33.99	48.24	6.07	4.81	4.35	3.38	16.64	13.87	19.97	5.52
16	15	0.00	2	2	6.06	15.89	50.20	30.91	49.32	6.63	4.81	2.75	3.33	15.91	13.27	19.95	5.66
17	15	0.25	1	3	4.13	13.64	54.06	43.73	37.76	6.88	5.03	5.35	4.14	14.64	12.37	16.81	3.68
18	10	0.50	1	4	4.92	13.04	51.69	37.15	42.97	6.30	5.85	4.91	5.02	13.92	12.29	17.20	3.55
19	5	0.00	2	3	5.98	17.86	59.47	26.93	61.59	6.33	5.05	3.63	2.91	16.53	14.37	21.54	5.59
20	10	0.25	2	3	5.80	15.83	56.94	33.17	54.93	5.98	3.44	3.12	3.42	15.73	13.59	20.30	5.62
21	10	0.25	1	4	4.24	13.58	55.08	36.20	47.57	8.63	7.41	5.25	5.68	13.04	12.70	17.53	3.41
22	10	0.25	1	5	4.13	14.29	54.46	39.58	42.81	8.37	7.20	5.01	6.20	13.57	12.49	16.83	4.45

GA, gum Arabic; MCT, medium chain triglyceride; WVP, water vapor permeability ($g.s^{-1}.m^{-1}.Pa^{-1}$); MC, moisture content (%); WS, water solubility (%); IC_{50}, DPPH radical scavenging capacity ($\mu g.ml^{-1}$); TPC, total phenolic content (µg gallic acid equivalents per mg film); PV, *Pseudomonas viridiflava*; BS, *Bacillus subtilis*; RD, *Rhodotorula diobovata*; AA, *Alternaria alternata*; values are means (n = 3).

(W_0). The pieces were then dried at 105 °C (U10, Memmert, Schwabach, Germany) to constant mass (W_1). The moisture content was calculated using the following equation (Alves et al., 2018):

$$Moisture\ content\ (\%) = \frac{W_0 - W_1}{W_0} \times 100 \quad (3)$$

The dried film specimens (W_1) were placed in 100 ml containers with 50 ml ultrapure water, which was agitated at room temperature for 5 h. The films were then filtered using previously weighed filter papers and dried at 105 °C until constant weight (W_2). The film solubility was calculated using the following equation (Farahnaky et al., 2013):

$$Film\ solubility\ (\%) = \frac{W_1 - W_2}{W_1} \quad (4)$$

2.3.4. Fourier transform infrared spectroscopy

The Fourier transform infrared (FT-IR) spectra of the films and the ingredients (i.e., gum Arabic, MCT oil, freeze-dried extracts) were recorded using a Bruker FT-IR spectrophotometer (ALPHA II, Bruker Optics, Ettlingen, Germany). All FT-IR spectra were collected with 24 scans in the spectral range of 400–4000 cm^{-1} with a resolution of 4 cm^{-1}.

2.4. Functional properties of edible coating/film

2.4.1. Antioxidant capacity

In order to conduct the antioxidant assays, the film extract was prepared by dissolving 25 mg of film sample in 3 ml of ultrapure water (Siripatrawan & Harte, 2010). DPPH (2,2-diphenyl-1-pikryl-hydrazyl) reduction assay was carried out by mixing equal aliquots of ethanolic DPPH (Sigma-Aldrich, St Louis, MO, USA) solution (0.1 mM) and film extract and reading the absorbance at 517 nm after 30 min of dark incubation at room temperature (Brand-Williams et al., 1995). Data were reported as IC_{50} ($\mu g.ml^{-1}$) as the mean of triplicate. Total phenolic content (TPC) of the film samples was determined using the Folin-Ciocalteu method (Singleton et al., 1999). Briefly, 20 µl of the film extract was mixed with 100 µl of Folin-Ciocalteu reagent (Sigma-Aldrich). After 1 min incubation, 300 µl sodium carbonate solution (20%; Chem-Supply, Gillman, SA, Australia) was added and volumed up to 2 ml by ultrapure water. The absorbance was read at 760 nm after 2 h incubation in dark at room temperature. Gallic acid (Sigma-Aldrich) was used as a standard and data were reported as µg gallic acid equivalent per mg film (as the mean of triplicate).

2.4.2. Antimicrobial activity

The antimicrobial activity of the edible coatings and films was determined using well-diffusion and disc-diffusion methods (Clinical & Institute, 2012), respectively, against *Pseudomonas viridiflava*, *Bacillus subtilis*, *Rhodotorula diobovata* and *Alternaria alternata*, which were taken from a culture collection of the University of Queensland (Coopers Plains, QLD, Australia). Briefly, the inoculums of bacteria and yeast were prepared from overnight grown cultures and the mold inoculum from 5-day old culture in saline by adjusting the absorbance to 0.08–0.10 at 600 nm (10^6 CFU ml^{-1}). An 8-mm well was made on the inoculated Mueller Hinton agar (MHA; Oxoid, Hampshire, England) plates and followed by inserting 100 µl of the coating solution. On the other hands, the films were aseptically cut into 8-mm discs and weighed, and then laid onto the inoculated MHA plates. The plates were incubated at 25 °C for 48 h for fungi and 30 °C for 24 h for bacteria and the inhibitory zone (mm) was measured by a digital caliper. The antimicrobial activity was reported as the zone of inhibition in mm per 100 µl of the coating solution or 10 mg of the edible film. The sensitivity according to diameter of inhibition zone can be categorized as follows: <8 mm not sensitive, 9–14 mm sensitive, 15–19 mm very sensitive, >20 mm extremely sensitive (Djenane et al., 2011).

2.5. Experimental design

The interactive effects of extracts, gum Arabic and MCT oil concentrations on the antimicrobial and physicochemical properties of the edible coating were evaluated and optimized using RSM. An I-optimal design was used to determine the effects of three independent including two numerical factors in three levels and one categorical factor (i.e.,

extract blends) in two levels. The Design Expert software (v.11.1.2.0, Statease Inc., Minneapolis, MN, USA) was used to generate the RSM design, regression analysis of experimental data, and to depict the perturbation and interaction plots to demonstrate the interactive effects among variables. The design matrix and actual responses are given in Table 1.

2.6. Application of edible coating on fresh-cut red capsicum

Commercially mature red capsicums (*Capsicum annuum*) were obtained from a local grower (W&L Farms, Bundaberg, QLD, Australia). Capsicums were sorted based on color, size and absence of fungal decay or mechanical damage. They were then sanitized by 2-min immersing in a 2% (v/v) food-grade sodium hypochlorite solution, followed by rinsing with reverse osmosis (RO) water, draining, and air-drying at room temperature. Subsequently, capsicums were cut lengthwise into 1 cm × 8 cm sticks. The capsicum sticks were then divided randomly into four groups, with each group containing 240 sticks. The groups were assigned to three different treatments: (i) no dipping (uncoated), (ii) 2-min dipping in extract-free coating solution (coating control), and (iii) 2-min dipping in antimicrobial coating solution (coated). The application ratio of the solution to the capsicum sticks was 1:1 (w/w). After draining, the sticks were air-dried for 30 min using a cabinet air drier (30 °C, 4 m/s air speed; Lindner & May, QLD, Australia). Next, five capsicum sticks were placed in an oriented-polystyrene package (OPS YS-1H, Yi Shen Plastic Corp., Changhua County, Taiwan), with each package serving as a replicate. There were six replicates per treatment. Data were collected at day 1 and at 3-day intervals for 16 days of storage at 4 °C and 90 ± 3% relative humidity. On each sampling day, six packages per treatment were randomly selected for destructive measurements once the capsicum sticks reached room temperature. Additionally, another set of fresh-cut red capsicums with eight replicates per treatment was stored under the same conditions to evaluate changes in weight loss.

2.6.1. Weight loss and firmness

The weight loss of fresh-cut capsicums was determined as the fruit weight difference between the initial and specific time intervals and results expressed as a percentage loss of the initial weight. The firmness value (N) as the maximum penetration force was determined by a texture analyzer (TA1, Lloyd materials testing, Ametek Inc., Largo, FL, USA) using a 6-mm-diameter cylindrical stainless steel flat probe (3 mm, 0.5 mm s^{-1}).

2.6.2. Total soluble solids and titratable acidity

The total soluble solids (TSS) and titratable acidity (TA) were determined according to the AOAC methods 932.12 and 942.15 (*AOAC, 1995*), respectively. Four capsicum sticks were taken randomly from six packages and were homogenized in a ball mill (20 s, 30 s^{-1}; MM400, Retsch, Haan, Germany). About 2 g of the puree was centrifuged (13, 000 rpm, 5 min, 25 °C; 5415D, Eppendorf, Hamburg, Germany) and supernatant was used to measure the TSS by a digital refractometer (PAL-1, Atago, Tokyo, Japan) and was expressed as °Brix. Ten grams of the puree were diluted with 100 ml distilled water, which was used to determine TA by titrating with 0.1 N NaOH (Chem Supply, Gillman, SA, Australia) to pH to 8.2 using an automatic titrator (765 Dosimat, Metrohm, Herisau, Switzerland) and the result was expressed as a percentage of citric acid.

2.6.3. Microbiological quality

Ten grams of samples were aseptically and randomly taken from two packages, transferred into sterile sampling bag, and 90 g of tryptone water (0.1% w/v; LP0042, Oxoid) was added. The capsicum homogenate was then prepared by 1-min mixing using a stomacher (BA6021, A. J. Seward & Company Limited, London, UK). The suspension was ten-fold diluted and was either pour-plated using plate count agar (PCA; Oxoid) for mesophilic bacteria (30 °C, 72 h) or spread-plated onto Dichloran Rose Bengal Chloramphenicol (DRBC; CM0727, Oxoid) agar for yeast and mold (25 °C, 72 h). The results were expressed as logarithms of colony-forming units per gram of capsicum sticks ($\log_{10}$ (CFU. g^{-1})).

2.6.4. Sensory evaluation

The overall acceptance of the coated fresh-cut capsicums was evaluated after treatment (day 0) by a benchtop testing. The panel involved thirteen staff from the Centre for Nutrition and Food Sciences (QAAFI, UQ, QLD, Australia) and Department of Agriculture and Fisheries (Health and Food Sciences Precinct, Coopers Plains, QLD), aged between 19 and 61 years old (5 male and 8 female), who were familiar with fruit sensory evaluation (UQ Human Research Ethics approval number 2018000107). Panelists were asked to rate the degree of liking on an unstructured linear scale from greatest imaginable dislike (=0%) to greatest imaginable like (=100%) for the following attributes appearance, color, aroma, flavor, texture, after taste and feel, overall acceptance and intention to purchase the product.

2.7. Statistical analysis

The statistical analysis of the data was done by ANOVA at a 5% significant level (p-value), and the effect and regression coefficients of individual linear, quadratic and interaction terms were determined (Design Expert, v.11.1.2.0). The quality-of-fit was determined using the coefficient of determination (R^2) and the statistical significance of the model equation was determined using the F-test. To validate the model, the observed values of diameter of inhibition zone (mm) of the optimized formulation were compared with the model-predicted ones. SPSS statistical software (IBM SPSS 27, SPSS Inc., Chicago, IL, USA) was used to compare the mean values by one-way ANOVA and Tukey's tests at the 5% significance level. All the experiments were done in at least three replications.

3. Results and discussion

A randomized I-optimal polynomial design was performed to investigate the individual and interaction effect of the three factors (i.e., gum Arabic concentration, MCT oil concentration and extract blends) used in edible coating preparation on its antimicrobial properties. The experimental runs and corresponding response values are presented in Table 1. The significance and adequacy of developed models and the influences of independent variables and their interactions on the studied parameters are judged by ANOVA presented in Table S2 and Table S1. The values for coefficient of determination (R^2) were 0.67–0.94, indicating the proper prediction ability of the models (Table S2, Figs. S1–S4). The reliability of the predicted models is further confirmed by lack-of-fit test, in which the p-value of fitted models for all responses should not be significant ($p > 0.05$).

3.1. Film properties

3.1.1. Opacity, water vapor permeability, moisture content and water solubility

The transparency of coatings and edible films determines their acceptability among consumers. The ability of coatings to preserve products relies on their capacity to protect against deterioration caused by light. This protective property, known as the light barrier property, can be measured through opacity. Table 1 presents the interactive effect of independent factors on the opacity values. The range of opacity values obtained was between 2 and 5 au. mm^{-1}, with the lowest value (2 au. mm^{-1}) observed at the highest gum Arabic concentration (15%) in the presence of extract blend 2 (Table 1), as is shown in the interaction plots (Fig. 1). Our findings indicate that the films were opaque due to interactions between the components and the presence of colored pigments in the extracts. The linear model predicting opacity highlights

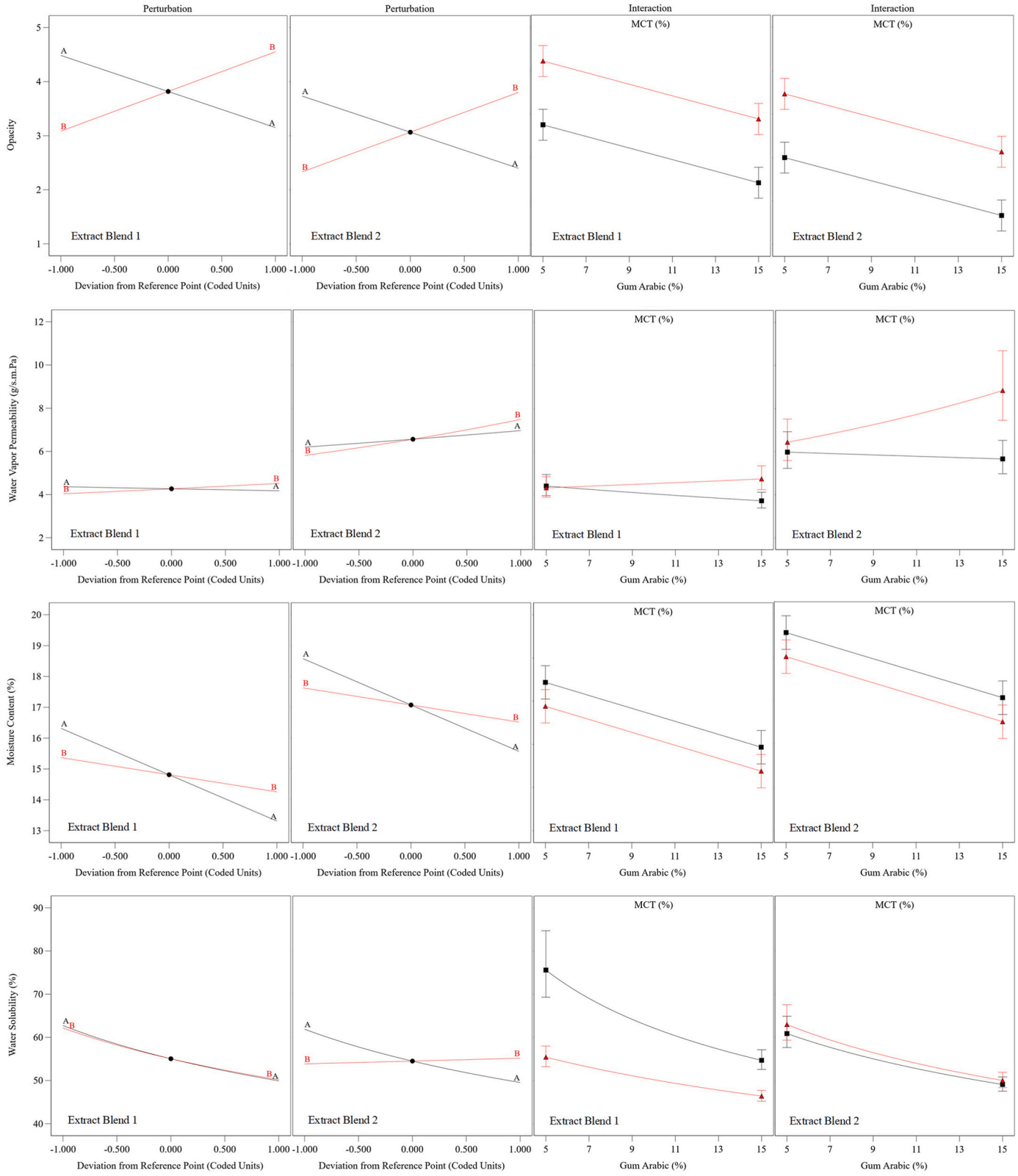

Fig. 1. Perturbation and interaction plots showing the effects of independent variables on opacity, water vapor permeability, moisture content, and water solubility of edible films. A, gum Arabic; B, MCT oil; ■, 0% MCT oil; ▲, 0.5% MCT oil. Actual factors (perturbation plot): 10% gum Arabic, 0.25% MCT oil.

that the concentration of gum Arabic and MCT oil significantly ($p < 0.05$) contribute to the transparency of the coating (Table S3). Perturbation plots demonstrated that opacity significantly ($p < 0.05$) increased with higher concentrations of MCT oil, while an increase in gum Arabic concentration leads to a significant ($p < 0.05$) reduction in transparency (Fig. 1). It is speculated that high concentrations of gum Arabic result in a continuous network formed by increased intra/inter-molecular interactions with extracts, particularly in the absence of MCT oil (Pena

Serna & Lopes Filho, 2015). High concentrations of gum Arabic may also dilute the extracts (Vanin et al., 2005), enhancing light transmission and resulting in lower opacity values. Conversely, higher opacity values in the presence of MCT oil could be attributed to increased light scattering (Atarés & Chiralt, 2016) or the non-polar nature of the coating solution. Furthermore, the presence of hydrophilic compounds in non-polar environments could promote their separation and precipitation, leading to a dense and heterogeneous matrix with aggregated compounds that act as a barrier to light transmission (Pena-Serna & Lopes-Filho, 2013). The colored pigments present in the extract also contribute to the opacity of the coating film layers, but their interactions with other constituents of the coating can vary, resulting in different opacity levels across formulations (Fig. 1).

The ability of a coating to preserve fresh produce by minimizing its moisture loss depends on its water vapor permeability (WVP), which is influenced by the thickness and constituents of the coating. Generally, a lower WVP indicates better preservation by reducing moisture loss (Ma et al., 2008). The WVP values of the obtained edible films ranged from 0.34 to 0.98 ($\times 10^{-6}$) $g.s^{-1}.m^{-1}.Pa^{-1}$ (Table 1), and no significant ($p > 0.05$) effect of gum Arabic on WVP was observed (Fig. 1; Table S3). However, significantly ($p < 0.05$) lower WVP was observed using extract blend 1 compared to extract blend 2 (Fig. 1), suggesting that the mass content of extracts in the coating formulation affects WVP. The addition of *D. bracteata* extract to blend 2 could contribute to higher WVP values in those formulations. This can be attributed to the hygroscopic nature of *D. bracteata* and *S. aqueum* extracts, which contain sugars and organic acids (Farahnaky et al., 2016), leading to increased wetting of the film surface on the high humidity side. Furthermore, an increase in MCT oil concentration resulted in a significant ($p < 0.05$) increase in WVP (Fig. 1). This contradicts our hypothesis of WVP reduction by adding MCT oil as a hydrophobic agent, as it actually acted as a plasticizer and negatively affected WVP (Tran et al., 2020). Glycerol addition has also been reported to increase molecular mobility, contributing to water vapor diffusion through the film (Maran et al., 2013).

Moisture content plays a crucial role in the ability of the coating to maintain moisture in fresh produce and its stability under varying humidity environments. The observed moisture content values ranged from 13.04% to 19.72% (Table 1), which aligns with reported values for plasticized biodegradable films (Suyatma et al., 2005; Tran et al., 2020). MCT oil had no significant ($p > 0.05$) impact on moisture content, while the other two components showed a significant ($p < 0.05$) effect (Fig. 1, Table S3). Increasing the gum Arabic concentration and using extract blend 1 resulted in lower moisture content, as illustrated in both perturbation and interaction plots (Fig. 1). A higher mass content of extracts (blend 2) led to a higher moisture content, likely due to the hydrophilic/hygroscopic nature of the extracts and their hydrogen bonding with free OH groups (Cerqueira et al., 2012).

The solubility of an edible coating/film in water determines its breakdown during consumption and biodegradation (Laohakunjit & Noomhorm, 2004). The water solubility values of the films ranged from 44.90% to 80.52%, with the highest value obtained at 5% gum Arabic with extract blend 1 in the absence of MCT oil (Table 1, Fig. 1). Water solubility characterizes the water resistance capacity of the edible coatings/films, where lower values indicate higher water resistance and lower water affinity. The ANOVA showed that the individual factors had a positive effect on water solubility, while the interaction of MCT oil and the extract blend negatively affected this parameter (Table S3, Fig. 1). It was observed that water solubility increased by reducing the gum Arabic and MCT oil concentrations in the presence of both extract blends (Fig. 1). This could be attributed to hydrophilic moieties in the extract disrupting the network formation by gum Arabic (Yuan et al., 2016), or the interaction between oil components (e.g., its aliphatic groups) and hydroxyl groups of the polysaccharide chain, reducing its availability to interact with water (Shojaee-Aliabadi et al., 2014). The solubility attributes of the edible coating/film may be desired or undesired depending on the application. For example, low solubility may be needed for foods with high moisture content or those stored in high humidity environments, while high solubility is required when the coated food will be consumed or cooked (Pena Serna & Lopes Filho, 2015).

3.1.2. FT-IR spectra

The FT-IR spectroscopy was used to study the intermolecular interactions between gum Arabic, MCT oil and plant extracts in the experimental films (Fig. 2). These interactions are characterized by shifts in absorption bands, indicating possible structural interactions and good miscibility of the partaking components in the coating matrices. The spectra of the components and the experimental films exhibited several peaks (Fig. 2), and the assignments for the spectra of components are provided in Table S1.

For the experimental films, a broad band in the range of 3300–3400 cm^{-1} was observed, corresponding to the O–H stretching vibration associated with intra-molecular hydrogen bonding formed by the hydroxyl groups of mono/polysaccharides and water (Gopi et al., 2019). This band was also present in the spectra of the components, albeit with lower intensity, except for MCT oil. The band around 2800–3000 cm^{-1} was assigned to symmetric/asymmetric stretching vibrations of the C–H bond in the aliphatic $–CH_2$ group (Rakmai et al., 2017), primarily due to the addition of MCT oil to the matrix.

Furthermore, the spectral region between 780 and 1450 cm^{-1} corresponds to the presence of carbohydrates (Şen & Erboz, 2010), ester sulphate groups characteristic of sulphated polysaccharide compounds (Pereira et al., 2009), and organic acids (Şen & Erboz, 2010) in the wavenumber ranges of 700–1000 cm^{-1}, 800–950 cm^{-1}, and 1000–1450 cm^{-1}, respectively. These characteristic absorption bands were observed in the spectra of the components and appeared in the spectra of the experimental films with the addition of the extracts to the gum Arabic matrix (Fig. 2). For instance, two absorption bands around 1320–1420 cm^{-1} for O–H bending and 1060–1150 cm^{-1} for C–O stretching are assigned to organic acids containing an alcohol functional group in their molecular structure (Moreira & Santos, 2004). Therefore, the absorption bands at 1400 and 1190 cm^{-1} in the *D. bracteata* spectrum can be associated with CH_2 vibration and O–H bending, respectively, which are identified as citric acid and malic acid (Max & Chapados, 2004).

Additionally, an absorption band from 900 to 1100 cm^{-1}, observed in all three extracts' spectra and more pronounced in *S. aqueum* (1099 cm^{-1}) and *D. bracteata* (shoulder at 1095 cm^{-1}), can be assigned to C–O valence vibrations, C–O–C stretching vibrations and C–O–H bending due to β-anomeric configuration of carbohydrates such as fructose and glucose (Kodad et al., 1994; Zhang et al., 2015). Moreover, the absorption bands centered at 1373 and 1264 cm^{-1} in *T. lanceolata* extract are associated with C–H and O–H bending, respectively, and thus assigned to sucrose (Kodad et al., 1994). However, there were slight shifts in the characteristic absorption peaks in the experimental films, indicating possible intermolecular interactions between the components and their miscibility in the coating matrices.

3.1.3. Antioxidant capacity

The values of DPPH IC_{50} and TPC of the edible films ranged from 26.36 to 43.73 μg ml^{-1} and from 36.30 to 63.46 μg gallic acid equivalents per mg film, respectively (Table 1). The antioxidant capacity of the edible films was significantly ($p < 0.05$) influenced by the linear effects of the extract blend and gum Arabic concentration, as shown in Table S3. This effect is also evident in the perturbation and interaction plots, indicating that the antioxidant capacity is dependent on the dose of the extracts and gum Arabic (Fig. S6). Gum Arabic exhibited a noticeable slope in this regard. However, MCT oil had a relatively lower impact on the antioxidant properties of the edible film ($p > 0.05$). The highest antioxidant capacity (IC_{50} of 26.36 μg ml^{-1} and TPC of 63.46 μg gallic acid equivalents per mg film) was observed with 5% gum Arabic and 5% MCT oil in the presence of extract blend 2. These results can be attributed to the high antioxidant efficiencies of extracts, as reported in

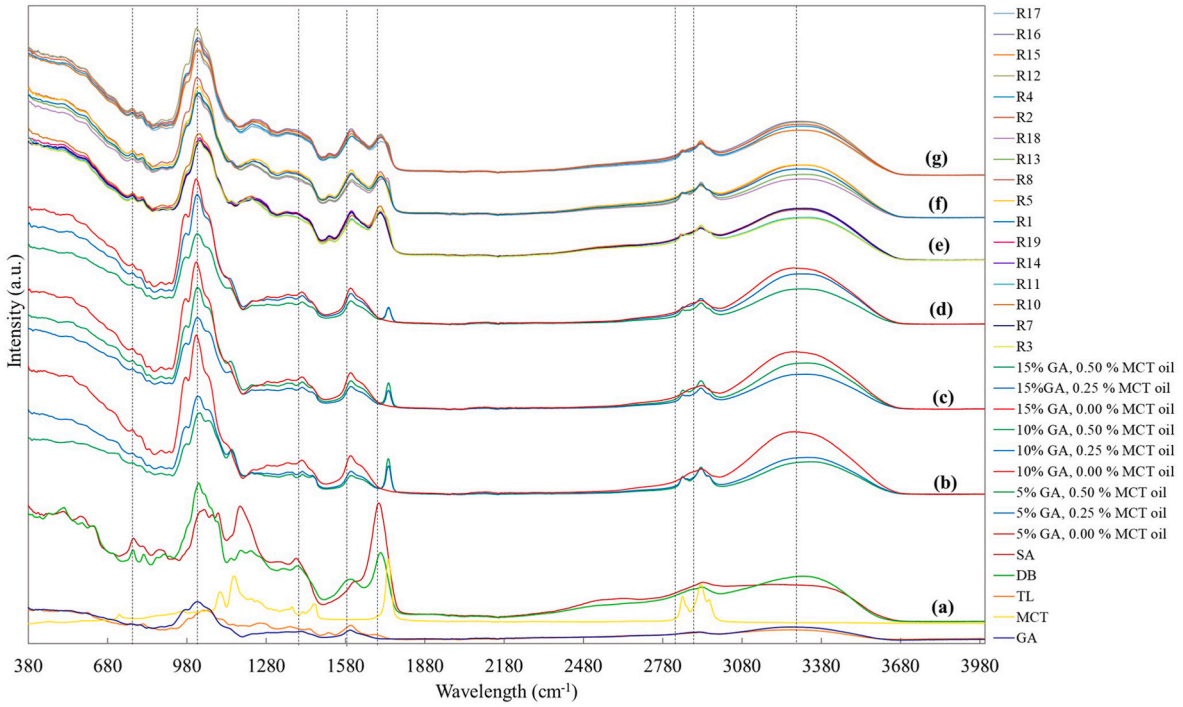

Fig. 2. FT-IR spectra of (a) each component, controls with (b) 5%, (c) 10% and (d) 15% gum Arabic, and experimental films with (e) 5% (including R3, R7, R10, R11, R14, R19), (f) 10% (including R1, R5, R8, R13, R18) and (g) 15% (including R2, R4, R12, R15, R16, R17) gum Arabic. GA, gum Arabic; MCT, medium chain triglycerides; TL, *Tasmannia lanceolata*; DB, *Diploglottis bracteata*; SA, *Syzygium aqueum*; R, experimental runs (refer to Table 1 for the formulations).

previous work (Seididamyeh et al., 2023), especially the *T. lanceolata* extract present in extract blend 2. The presence of plant extracts with secondary metabolites, such as phenolic compounds, enriches the coating and facilitates redox reactions. These reactions can occur in the plasma membrane of microbial cells, disrupting their respiration process by sequestering electrons (Kwon et al., 2007), thereby contributing to the antimicrobial properties of the coating.

3.1.4. Antimicrobial activity

To assess the antimicrobial capacity of the edible coatings and the effects of partaking components, perturbation and interaction plots were analyzed based on predictive quadratic models (Table S3; Fig. 3). The graphs revealed that the antimicrobial properties of the coating solutions increased with higher extract content and lower concentrations of gum Arabic and MCT oil (Fig. 3). However, the impact of the partaking components on the inhibitory activity against *A. alternata* was insignificant ($p > 0.05$), except for the extract blend, as indicated by a relatively flat line in the perturbation and interaction plots (Fig. 3d). Extract blend 2, containing a higher amount of *T. lanceolata* extract compared to extract blend 1, exhibited stronger inhibition against the mold. The antimicrobial efficacy of *S. aqueum*, *D. bracteata*, and *T. lanceolata* was previously reported (Seididamyeh et al., 2023), which was attributed to the presence of organic acids and non-anthocyanin polyphenols. In our previous study, the non-anthocyanin phenolic compounds as well as the organic acids in the studied extracts were identified (Seididamyeh et al., 2023). Table 2 presents the potential compounds that can attribute to the observed antimicrobial activity. The coatings with the highest inhibition against the tested microorganisms were those containing 5% gum Arabic, 0–0.25% MCT oil, and extract blend 2. Extract blend played a significant role, promoting a positive effect, where higher contents of extract in the edible coating solution favored maximal microbial inhibition due to the high antibacterial activity of *S. aqueum* and *D. bracteata* as well as moderate antifungal properties of *T. lanceolata* (Seididamyeh et al., 2023).

Furthermore, the steep curvature of the factors indicated that the inhibitory activity of the coating solution against *P. viridiflava* was influenced by the concentration of the partaking components in the coating matrix (Fig. 3a). However, ANOVA results demonstrated no significant ($p > 0.05$) effect of gum Arabic and MCT oil on the inhibitory activity against *P. viridiflava*, while both the linear and quadratic effects of the extract blend were significant ($p < 0.05$) (Table S3). Overall, reducing the gum Arabic concentration increased the inhibitory activity against *P. viridiflava* (Fig. 3a), *B. subtilis* (Fig. 3b) and *R. diobovata* (Fig. 3c). This can be attributed to the encapsulating effect of gum Arabic, where a higher concentration reduces the accessibility of the antimicrobial compounds in the extract to the microorganisms. Additionally, the addition of MCT oil to the coating matrix negatively affected the inhibitory activity against *R. diobovata*, as shown in the interaction plots (Fig. 3c).

The inhibitory effect of edible films was also evaluated to understand the antimicrobial activity of the coating solutions after drying and forming a thin film layer on the surface of fresh produce (Fig. S7). Moderate inhibitory activity was observed after drying, with the highest inhibition zone (6–11 mm per 10 mg of edible film) against *P. viridiflava*, the main spoilage microorganism in capsicum (Table S2). This can be attributed to the slow release of phytochemicals from the extract during incubation. The linear and interactive effects of the extract blend and MCT oil concentration significantly ($p < 0.05$) affected the inhibitory activity against *P. viridiflava*, while the linear effects of gum Arabic and extract blend had a significant ($p < 0.05$) impact on inhibiting *B. subtilis* (Table S3). In contrast to the coating solutions, higher inhibitory activity was observed in formulations containing extract blend 1. The possible reactions between gum Arabic and the higher amounts of sugars (i.e., sucrose, glucose, and fructose) in the extract blend 2 may result in better encapsulation of the bioactives and slower release during storage. Reducing both MCT oil and gum Arabic concentrations significantly ($p < 0.05$) increased antimicrobial activity (Fig. S7), potentially due to better accessibility of the bioactive compounds. However, higher concentrations of MCT oil in edible films slightly enhanced the antifungal activity against *R. diobovata* and *A. alternata* (Figs. S7c and d). This can

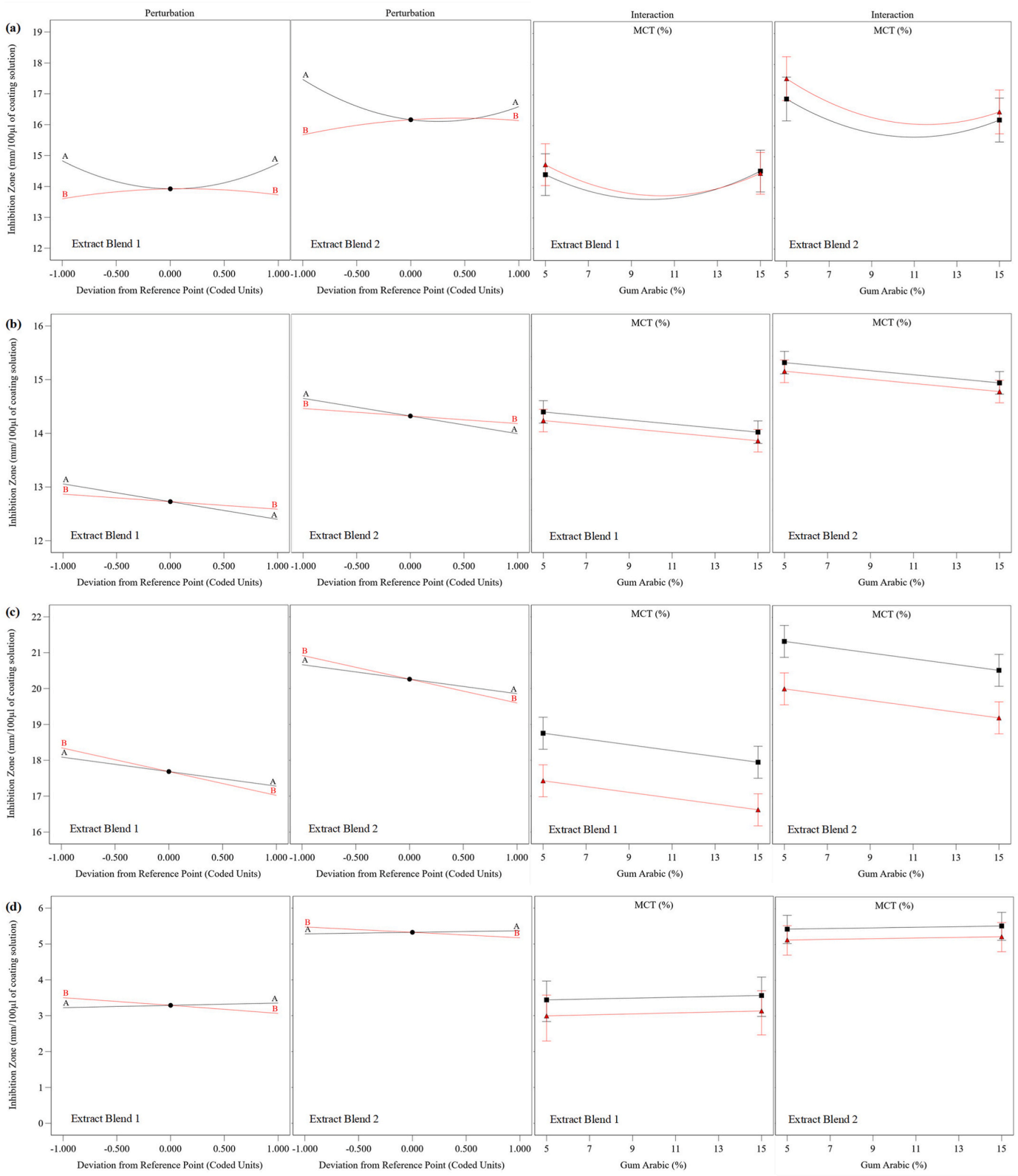

Fig. 3. Perturbation and interaction plots showing the effects of independent variables on inhibition zones of edible coating solution against (a) *Pseudomonas viridiflava*, (b) *Bacillus subtilis*, (c) *Rhodotorula diobovata*, and (d) *Alternaria alternata*. A, gum Arabic; B, MCT oil; ■, 0% MCT oil; ▲, 0.5% MCT oil. Actual factors (perturbation plot): 10% gum Arabic, 0.25% MCT oil.

Table 2
The potential antimicrobial compounds tentatively identified in the extracts (Seididamyeh et al., 2023).

Tasmannia lanceolata	Diploglottis bracteata	Syzygium aqueum
Shikimic acid	Malic acid	Malic acid
Procyanidin dimer (B-type)	Coumarin derivative	Citric acid
Chlorogenic acid	Procyanidin dimer (B-type)	Quinic acid
Rutin	Catechin	Gallic acid
Chlorogenic acid dimer	Catechin glucoside	Castalagin
4-*O*-*p*-Coumaroylquinic acid	Epicatechin	Bergenin
Quercetin-3-*O*-glucoside		Cyanidin-3-glucoside
Vitexin		Kaempferol hexoside
Isovitexin		(epi)Gallacatechin gallate
Luteolin hexoside		Theasinesin A quinone
Apigenin dihexoside		Casuarinin
Apigenin		Vitexin/Isovitexin
Apigenin-7,4′-dimethyl ether		Ellagic acid
Quercetin		Phloretin-3′,5′-di-*C*-glucoside
		Quercetin-3-glucoside
		Myricetin glucoside
		Quercetin pentoside
		Phloridzin
		Myricetin
		Quercetin

be attributed to the hydrophobic nature of MCT oil, which may facilitate the penetration of bioactive compounds into the microbial cells.

The aim of this step was to develop a coating formulation using gum Arabic, MCT oil, and an extract blend containing aqueous extracts of *S. aqueum*, *D. bracteata*, and *T. lanceolata*, with maximum antimicrobial capacity, particularly against *P. viridiflava*, as well as minimum water vapor permeability to protect coated fruits from moisture loss. Based on the mathematical models and the desirability function approach using Design Expert software, the optimal formulation was selected, meeting the requirements of a coating with maximum antimicrobial capacity and minimum water vapor permeability. The optimal coating formulation contained 5% gum Arabic, 0.13% MCT oil and extract blend 2. The predicted and experimental antimicrobial values using the optimized formulation are presented in Table S5.

3.2. Effect of edible coating on fresh-cut red capsicum during storage

3.2.1. Quality attributes

The effect of an antimicrobial edible coating on the shelf life of fresh-cut capsicum was evaluated by analyzing weight loss, firmness, titratable acidity (TA), total soluble solids (TSS), and microbial analysis. The results are presented in Table 3 and Fig. 4. Weight loss in fruits is primarily caused by a combination of internal water loss through transpiration and tissue respiration. Fresh-cut capsicums are particularly susceptible to moisture loss due to the absence of protecting layers and wound-related phenomena, which leads to softening, shrinkage, microbial/chemical deterioration, and fading of surface color. The water loss property of fruits depends on the vapor pressure differential between the internal tissue and the surrounding atmosphere. Coating suspensions create a thin layer on the fruit surface, reducing moisture loss, inhibiting microbial attacks, and providing minor mechanical injury protection. Table 3 compares the weight loss of uncoated fresh-cut capsicums to coated capsicums with and without the extract blend in the coating solution. The antimicrobial edible coating had no significant ($p > 0.05$) effect on moisture loss in capsicums. This may be attributed to the high concentrations of extracts in the coating matrix, which created difficulties in the proper drying of the coating on the surface of capsicum sticks. This issue could be addressed by adding another polysaccharide to the formulation to increase the entanglement of the suspension networks, resulting in slower water vapor diffusion, lower permeability, and reduced water loss (Dong et al., 2015).

Firmness is a crucial quality parameter indicating the freshness of fresh-cut vegetables. Minimally processed fruits and vegetables have a short shelf-life due to rapid firmness loss caused by moisture loss during storage. Changes in the firmness of control and coated fresh-cut capsicums during storage are presented in Table 3. Firmness values decreased over time, but there was no significant ($p > 0.05$) difference between the treatments. Polysaccharide-based coatings, including gum Arabic, have demonstrated the ability to maintain the firmness and moisture of fresh-cut produce by forming hydrogen bonds with molecules such as pectin on the surface of fruits and vegetables (Kurek et al., 2021). This barrier effect controls water vapor exchange and enzymatic reactions, leading to delayed weight loss and softening of the produce. However, the increase in firmness observed in coated samples (Table 3) may be attributed to the occurrence of an elastic state in the capsicum surface cells, which could be related to exposure to excess moisture and solutes in the extracts. The diffusion of extracellular water molecules from inside to the capsicum surface helps to equalize the solute concentrations within and outside the cells. This process can also affect the turgor pressure of cell walls within capsicums, potentially leading to tissue softening. Consequently, penetrating the rubbery capsicum tissue becomes more difficult, requiring higher force. Further studies are necessary to address the drying issue of the coating formulation while maintaining its established antimicrobial properties. This could be achieved by partially substituting the extracts with the organic acids identified in the extracts and exploring the applicability of spray coating to reduce the amount of coating solution applied to the fruit.

Table 3
Changes in weight loss, firmness, titratable acidity (TA), and total soluble solids (TSS) of fresh-cut red capsicums during storage at 4 °C.

	Treatment	Storage Days					
		1	4	7	10	13	16
Weight Loss (%)	Uncoated	-	0.65 ± 0.54^{aA}	2.01 ± 0.84^{abA}	2.63 ± 1.03^{bcA}	3.45 ± 1.09^{cdA}	4.44 ± 1.13^{dA}
	Coating Control	-	0.72 ± 0.71^{aA}	2.12 ± 0.84^{bA}	2.74 ± 0.90^{bcA}	3.43 ± 0.82^{cdA}	4.23 ± 1.05^{dA}
	Coated	-	0.56 ± 0.12^{aA}	2.28 ± 0.48^{bA}	3.09 ± 0.66^{bcA}	3.88 ± 0.70^{cA}	4.78 ± 0.90^{dA}
Firmness (N)	Uncoated	13.70 ± 2.74^{bA}	12.49 ± 2.49^{abA}	11.46 ± 1.83^{abA}	12.16 ± 1.95^{abA}	12.07 ± 2.28^{abA}	11.29 ± 1.93^{aA}
	Coating Control	12.97 ± 1.93^{aA}	12.74 ± 3.03^{aA}	12.41 ± 2.13^{aAB}	12.29 ± 1.51^{aA}	11.72 ± 1.99^{aA}	11.71 ± 1.31^{aA}
	Coated	11.97 ± 1.63^{aA}	11.98 ± 2.44^{aA}	13.16 ± 1.59^{aB}	12.87 ± 1.96^{aA}	12.61 ± 2.59^{aA}	13.16 ± 1.66^{aA}
TA (%)	Uncoated	0.28 ± 0.02^{abA}	0.32 ± 0.01^{bcB}	0.26 ± 0.01^{aA}	0.32 ± 0.02^{bcB}	0.31 ± 0.02^{bcB}	0.32 ± 0.01^{cA}
	Coating Control	0.26 ± 0.01^{abcA}	0.25 ± 0.02^{abA}	0.24 ± 0.01^{aA}	0.28 ± 0.01^{bcA}	0.27 ± 0.01^{abcA}	0.29 ± 0.02^{cA}
	Coated	0.41 ± 0.02^{aB}	0.43 ± 0.02^{abC}	0.41 ± 0.02^{aB}	0.47 ± 0.00^{bC}	0.45 ± 0.01^{abC}	0.45 ± 0.03^{abB}
TSS (°Brix)	Uncoated	8.87 ± 0.75^{aA}	8.83 ± 0.35^{aA}	9.13 ± 0.51^{aAB}	8.93 ± 0.38^{aA}	9.20 ± 0.46^{aA}	9.13 ± 0.60^{aAB}
	Coating Control	8.60 ± 0.70^{aA}	8.63 ± 0.58^{aA}	8.63 ± 0.12^{aA}	8.50 ± 0.40^{aA}	8.63 ± 0.47^{aA}	8.60 ± 0.56^{aA}
	Coated	9.63 ± 0.12^{aA}	10.03 ± 0.25^{abB}	10.03 ± 0.06^{abB}	10.57 ± 0.29^{bB}	10.67 ± 0.40^{bB}	10.00 ± 0.20^{abB}

Data are mean ± standard deviation (weight loss, n = 8; firmness, TA, and TSS, n = 12); data with different small letters in the same row and different capital letters in the same column are significantly ($p < 0.05$) different. Treatments: uncoated, no dipping treatment; coating control, 2-min dipping in film-forming solution without extracts; coated, 2-min dipping in antimicrobial coating solution.

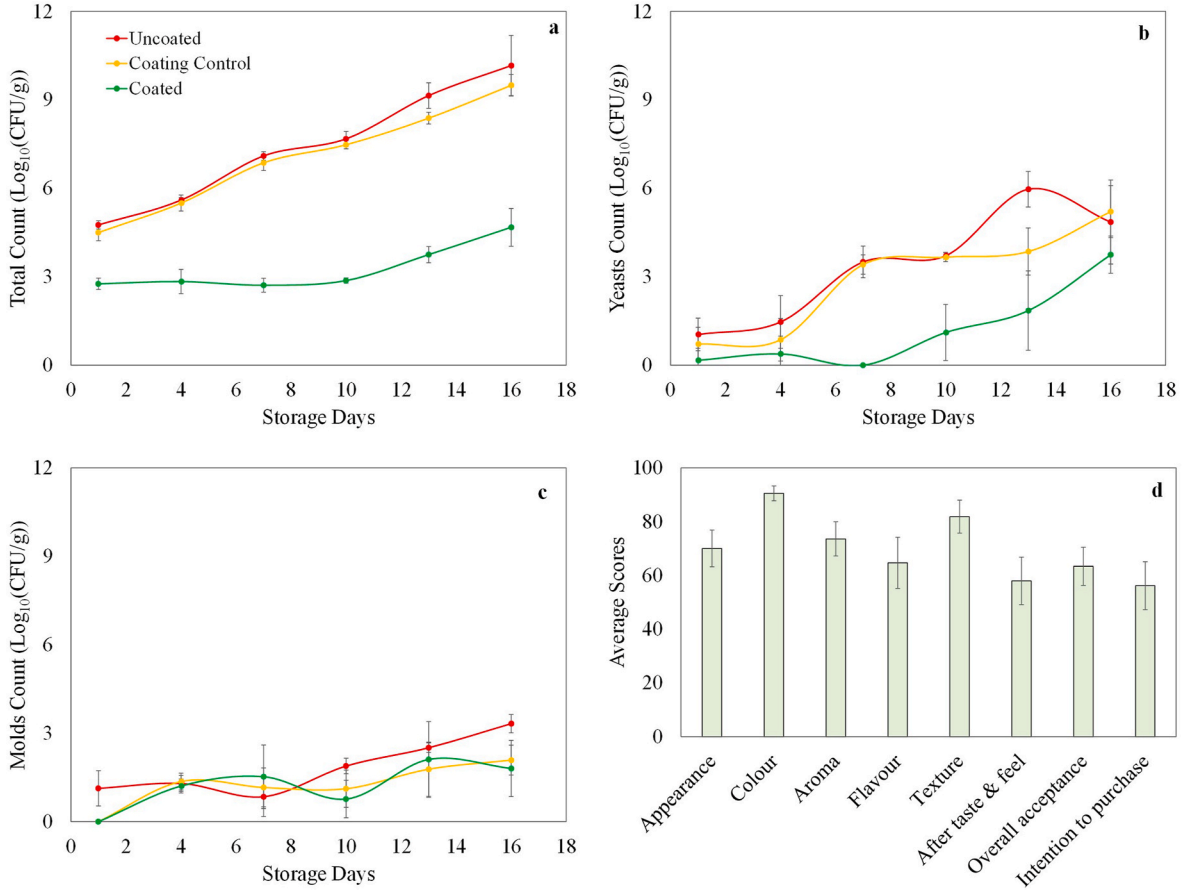

Fig. 4. Effect of different treatments on the total aerobic (a), total yeasts (b), and total mold (c) counts in fresh-cut red capsicums during storage at 4 °C; (d) average score of attributes for the coated fresh-cut red capsicum (benchtop testing; n = 13). Error bars indicate the standard deviation ($p < 0.05$).

One of the challenges in fresh-cut capsicums is the absence of common spoilage indicators such as browning, while changes in flavor, firmness and nutritional value occur due to subtle physiological decay combined with rapid microbial growth (Barrett et al., 2010). Acidity (TA) and TSS are essential components of overall fruit flavor and quality. A slight increase in TA and TSS values was observed in uncoated fresh-cut capsicums during storage (Table 3). However, coated capsicums had significantly ($p < 0.05$) higher TA and TSS values during storage compared to the two controls, which can be attributed to the organic acids and sugars present in the extract blend. Results showed an increase in TA and TSS values of coated capsicums after day 10 of storage. This increase could be related to the microbial growth (Fig. 4) and the utilization of sugars by microorganisms as a source of energy, leading to their conversion to organic acids and subsequent higher TA values. Additionally, various metabolic reactions can influence TSS values in fruits and vegetables during storage, including water loss, hydrolysis of sugars and acids, and solubilization of cell walls (Almenar et al., 2009). However, the utilization of sugars and acids in respiration can result in a decrease in TA or TSS values (Anthon & Barrett, 2012), as observed for TSS at the end of storage.

3.2.2. *Microbial count*

Spoilage of fresh-cut produce is primarily caused by microbial growth, resulting in off-flavors, off-aromas, and soft rot (Kaczmarek et al., 2019). Fresh-cut vegetables provide an ideal environment for various spoilage microorganisms due to their high moisture content, nutrient-rich composition (including structural polysaccharides like hemicellulose and pectin), and near-neutral pH (Miedes & Lorences, 2004). Bacterial soft rot, caused by psychrotrophic Pseudomonads, is a significant contributor to the short shelf-life of fresh-cut vegetables during refrigerated storage (Liao, 2005).

The antimicrobial effect of the applied coating on total aerobic bacteria (total count), yeasts and molds in fresh-cut red capsicums is presented in Fig. 4. The initial microbial counts (aerobic bacteria, yeasts, and molds) indicate the high susceptibility of fresh-cut produce to cross-contamination during preparation, including cutting after the washing step. This reflects the inefficiency of chemical washing of the whole fruits in maintaining microbial safety. To suppress microbial proliferation and extend the shelf-life of fresh-cut products, they should be stored at temperatures no higher than 5 °C (USDA, 2014). In the case of capsicums, the potential benefits of cold storage in retarding decay outweigh the possible damage by chilling injury.

Results showed an immediate and significant ($p < 0.05$) antimicrobial effect of the coating, with a 2 log CFU. g^{-1} decrease in total bacteria and approximately a 1 log CFU. g^{-1} decrease in total yeasts and molds on day 1, compared to the controls. This antimicrobial effect against total bacteria was maintained until day 10 of storage, with a bacterial load approximately 4 log CFU. g^{-1} lower than the controls (Fig. 4a). After day 10, the bacterial load in coated capsicums increased, but it remained 5 log CFU. g^{-1} lower than the control samples. Gómez-López and colleagues suggested a limit of 6 log CFU. g^{-1} for aerobic plate count in fresh-cut vegetables (Gómez-López et al., 2008). In this study, the coating with extracts was able to keep the bacterial count of fresh-cut capsicums below this limit during storage at 4 °C, reaching 4.68 log CFU. g^{-1} on day 16 of storage.

The coating demonstrated effective inhibition of yeast growth on fresh-cut capsicums, resulting in a significantly ($p < 0.05$) lower count of approximately 3 log CFU. g^{-1} lower ($p < 0.05$) compared to the control groups (Fig. 4b). However, no inhibitory effect against molds was observed ($p > 0.05$), which aligns with our previous *in vitro* findings

(Seididamyeh et al., 2023). Previous studies on fresh-cut capsicums have also explored the use of polysaccharide-based edible coatings for preservation purposes. For instance, a reduction of approximately 2 log CFU. g^{-1} in total aerobic bacterial load during cold storage was observed by coating fresh-cut yellow capsicums with chitosan nanoparticles resulted (Hu et al., 2020) and coating fresh-cut red capsicums with chitosan-tea tree oil nanoemulsion containing calcium chloride (Sathiyaseelan et al., 2021). Furthermore, other preservation techniques have been investigated, such as pulsed light treatment of red capsicum slices, which achieved a reduction of 1.59–2.13 log CFU. g^{-1} in total aerobic bacterial load during a 7-day storage period at 10 °C (Rybak et al., 2021).

The results of our study demonstrate the antimicrobial effectiveness of the developed coating against bacterial populations in fresh-cut capsicums both immediately after preparation and during prolonged refrigerated storage. This efficacy could be attributed to the high concentration of polyphenols and organic acids present in the bioactive extracts used in the coating's composition, which effectively inhibit bacterial growth. Furthermore, the ability of gum Arabic to encapsulate plant extracts has been demonstrated in literature (Sarabandi et al., 2019), and therefore we suggest that its encapsulating properties allow for a slow release of the bioactive compounds over time. This continuous release is likely facilitated by the hydrophilic nature of the polysaccharides, as they undergo hydration (Boumail et al., 2013).

3.2.3. Sensory evaluation

A benchtop evaluation was conducted using a panel of 13 assessors, consisting of 5 males and 8 females, to assess the sensory attributes of the treated fresh-cut red capsicums. Among the assessors, a significant majority (92%) favored red capsicums over green and yellow varieties and about half of them reported infrequent consumption of capsicums. The purpose of this testing session was to gain a preliminary understanding of how the applied coating affected the sensorial perception and overall liking of fresh-cut red capsicums. The average scores given to each attribute are depicted in Fig. 4d, and the comments provided by most panelists are presented in Table S6. Regarding the appearance attribute, the product received a 70 liking score, primarily due to the presence of excess moisture on the capsicum sticks, as indicated by the assessors' comments (Table S6). This "moist look" was a result of the drying issue associated with the coating on the capsicum surface, as previously mentioned. The aroma and flavor of the capsicum sticks were indeed influenced by the extracts added to the formulation as antimicrobial agents, resulting in liking scores of 74 and 65, respectively (Fig. 4d). The assessors perceived a peppery smell and heat, as well as a tart and sweet flavor, which were attributed to the *T. lanceolata*, *S. aqueum*, and *D. bracteata* extracts used in the coating. Overall, the coated capsicums received good acceptance rates of over 60, with about 56% of the assessors expressing an intention to purchase such a product. This acceptance was influenced by the added flavor to the capsicums. Consequently, the panelists unintentionally compared the coated capsicums with the raw one they typically consume as part of their diet. Therefore, it is suggested that in future studies, the coated capsicums should be introduced as a distinct new product, rather than being directly compared to the untreated ones.

4. Conclusion

The formulated gum Arabic edible coating suspensions, loaded with extracts, proved to be suitable as a postharvest treatment for fresh-cut red capsicums, primarily due to their strong antimicrobial capacity against the soft-rot causing microorganism, *P. viridiflava*. Response surface methodology was employed to investigate the impact of component concentrations on the properties of the edible coating/film and optimize the formulation with the highest antimicrobial capacity. The extensive antimicrobial activity of the edible coating was demonstrated by maintaining the total plate count at 2.8 log CFU. g^{-1} until day 10 of storage, after which it increased to 4.68 log CFU. g^{-1} by day 16. The coated capsicums exhibited a 4–5 log CFU. g^{-1} reduction in aerobic bacterial load compared to the uncoated capsicums during storage. However, the developed edible coating did not adequately retain product moisture and firmness, which are important quality attributes for fresh-cut vegetables. This issue can be addressed by incorporating additional polysaccharides into the coating to improve its structural properties. The developed edible coating offers an environmentally friendly solution for maintaining the microbial quality of fresh-cut capsicums. However, further research is required to address the freshness retention of fresh-cut capsicums to meet consumer expectations. Ultimately, the development of coated fresh-cut capsicums with extended shelf life and the added flavors of the *T. lanceolata*, *S. aqueum*, and *D. bracteata* plant extracts could introduce a new product to consumers (such as food service providers and retailers) that can be enjoyed as a healthy snack or used in salads.

CRediT authorship contribution statement

Maral Seididamyeh: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft. **Sandra Milena Olarte Mantilla:** Methodology, Writing – review & editing. **Michael E. Netzel:** Supervision, Writing – review & editing. **Ram Mereddy:** Supervision, Writing – review & editing. **Yasmina Sultanbawa:** Funding acquisition, Resources, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Yasmina Sultanbawa reports financial support was provided by University of Queensland. Yasmina Sultanbawa reports financial support was provided by Horticulture Innovation Australia Ltd. Yasmina Sultanbawa reports financial support was provided by Australian Research Council Industrial Transformation Training Centre for Uniquely Australian Foods.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodcont.2023.110267.

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