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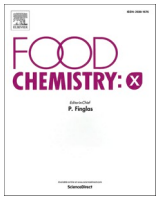

Impact of *Premna microphylla* Turcz leaf water extracts on the properties of gelatin-carrageenan edible film and its application in cherry tomatoes storage

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ABSTRACT

This study investigated the potential of enhancing edible film (EF) formulations by incorporating *Premna microphylla* Turcz leaf (PM) water extracts (PMWE) and glycerol as plasticizers. Incorporating 75 % PMWE and 5 % glycerol significantly improved the physicochemical and mechanical properties of the films while effectively preserving the quality indicators and extending the shelf-life of cherry tomatoes (CT; *Lycopersicon esculentum* Mill) in film and coating applications. The PMWE-based films and coatings reduced decay rates (from 80 to 36–52 %) and exhibited a statistically significant difference ($p < 0.05$) compared to the control group. These findings highlight the potential of PMWE as an effective ingredient in EF formulations, capable of extending shelf-life to 12–16 days, offering promising applications in packaging materials. However, further advancements are required to address the limitations and enable large-scale trials during the mass production stage. Expecting to achieve optimized process formulations and conditions for CT or other agricultural product packaging materials.

1. Introduction

Worldwide, more than 10,000 varieties of tomatoes serve as food for consumption. According to a survey report published by Research and Markets Co. (2024), the global trade in tomatoes (varieties of tomatoes include beefsteak, cherry, grape, Roma, green, heirloom, and tomatoes on the vine) is experiencing robust growth, with the market size projected to increase from US$174.7 billion in 2023 to US$233.13 billion in 2028, reflecting a compound annual growth rate (CAGR) of 5.7 %. The popularity and demand for tomatoes have substantially surged, owing to their dietary benefits of serving as a rich source of nutrients and boasting remarkable antioxidant properties (Tilahun et al., 2021). Specifically, the abundance of nutrients (including carotenoids, fiber, and vitamins) and the bioactive compounds (polyphenols) it possesses have been widely acknowledged for their remarkable potential to promote overall well-being (Kabir et al., 2020; Mocanu et al., 2022). It is noteworthy that tomatoes are susceptible to abnormal handling, shock loads, and vibration during transportation, storage, and marketing (Bremenkamp et al., 2021; Kabir et al., 2020; Mocanu et al., 2022).

Consequently, the efficient management of tomatoes to minimize post-harvest losses has garnered significant attention from pertinent industries and stakeholders who stand to benefit from this endeavor. The current initiatives focus on investigating and enhancing preservation methodologies involving natural compounds, bioproducts, and edible materials (Du et al., 2024; Khatri et al., 2020; Rather et al., 2022; Yavari Maroufi et al., 2021). Remarkably, these substances have been applied to edible packaging materials, such as EFs or coatings, to extend the shelf-life of the foods (Lee, Yu, Tsay, et al., 2024; Rather et al., 2022; Yu et al., 2024). All these implementations can serve as viable alternatives to food packaging by establishing a barrier (to impede the exchange of oxygen, light, and moisture), thereby safeguarding the food, mitigating quality deterioration (by preventing microbial intrusion and decay while delaying oxidation), and prolonging the shelf-life of the food product (Du et al., 2024; Rostamabadi et al., 2024; Sabu Mathew et al., 2024). In addition, considering the limitations and weaknesses of these approaches' mechanical, barrier, and antimicrobial properties,

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numerous reports are being made for modifying films and coatings with edible composite materials (such as starch, cellulose, xanthan gum, pectin, chitosan, carrageenan, sodium alginate, arabic gum, gellan gum, gelatin, and pullulan) (Abdillah et al., 2024; Chou et al., 2023; Rostamabadi et al., 2024; Sabu Mathew et al., 2024; Wei et al., 2024; Yang et al., 2024).

Moreover, incorporating natural bioactive compounds into EF formulations has also been reported to provide practical options to improve the flexibility and brittleness of EF (Arcan & Yemenicioğlu, 2011; Jiang et al., 2024; Li et al., 2023; Wei et al., 2024; Zioga et al., 2024). Nonetheless, phenolic compounds constitute a wealth of highly potent bioactive substances that can be readily extracted from various plant materials and agricultural by-products (Arcan & Yemenicioğlu, 2011; Wei et al., 2024). It has also received excellent success in developing EFs with composite pectin, gelatin, and carrageenan for controlling and releasing proanthocyanidins embedded in EFs and improving the mechanical, barrier, and antioxidant properties of films (Chou et al., 2023; Sabu Mathew et al., 2024; Wei et al., 2024; Zioga et al., 2024). Therefore, these practical applications can serve as a viable blueprint for using natural polymer substances in food packaging materials (Rostamabadi et al., 2024; Sabu Mathew et al., 2024). Concurrently, it satisfies consumers' expectations of decreasing plastic product use to minimize microplastics while improving environmental pollution (Lin, Huang, et al., 2023).

Therefore, this study was performed to develop potential EFs by incorporating different ratios of PMWE in the basic EF formulation (carrageenan and gelatin) while improving the hydrophilic, physicochemical, and mechanical properties of PMWE-prepared EFs with varying ratios of plasticizers (2.5–20 % glycerol). In addition, this study evaluated the possibility of applying both forms of PMWE EFs (film and coating) during the CT shelf-life (40 days). Multiple indicators are employed to evaluate the CTs' qualities during the shelf-life period, encompassing lycopene content, ascorbic acid content, weight loss (WL), color analysis, titratable acidity (TA), pH value, total soluble solids (TSS), moisture content, textural profile analysis (firmness and elasticity), and decay rate.

2. Materials and methods

2.1. Materials

The freshly harvested CTs at breaker stage were purchased from Dream Leader Saltland Tomato Garden (Tainan, Taiwan). PM leaves were obtained from Green Village (Emei Township, Hsinchu, Taiwan). Gelatin (food grade) was purchased from the Tehmag Foods Co., Ltd. (New Taipei City, Taiwan). κ-Carrageenan was purchased from GREAT STRONG Industries Limited (Taipei, Taiwan).

2.2. Preparation of water-extracted bioactive substances, edible films (EFs), and coating solution

The extraction of bioactive substances and the preparation of the samples were based on our team's previous study (Huang, Chen, Lin, & Huang, 2024), with slight modifications. The PM leaves were washed, dried, pulverized using a grinder (RT25, SHIN JENN International Co., Ltd., Taichung, Taiwan), and sieved (80 mesh). The resulting PM powder was stored in a desiccator. For extraction, PM powder was mixed with deionized water (DDW) at a 1:50 (*w/v*) ratio, centrifuged (1600 ×*g* for 20 min), and the supernatant (PMWE) was diluted with DDW (25, 50, 75, and 100 %), then heated to 40 °C. Carrageenan (1.2 %) and gelatin (0.6 %) were added and stirred at 50 °C for 30 mins. The mixture was poured into dishes, dried at 50 °C for 36 h, and stored at 25 °C for 12 h to form EF. For glycerol mixtures, glycerol was added in varying ratios (2.5, 5, 10, 15, and 20 %). The final EF formulation was 75 % PMWE, 1.2 % carrageenan, 0.6 % gelatin, and 5 % glycerol. The coating solution was identical to EF but maintained at 45 ± 2 °C to prevent gelation, applied using an airbrush (GYD-1000MDSC, GISON Machinery Co., Ltd., Taichung, Taiwan).

2.3. Measurement of physicochemical properties of edible film (EF)

2.3.1. Appearance color

The EF color measurements followed the method of Lee, Wei, Yu, et al. (2024) with minor modifications, using a colorimeter (NE-4000, Nippon Denshoku Industries Co., Ltd., Tokyo, Japan). Results included L^* (luminance, 0–100), a^* (positive for red, negative for green), and b^* (positive for yellow, negative for blue) values.

2.3.2. Thicknesses

EF thicknesses were measured following the methodology outlined by Huang, Cheng, Lu, et al. (2024). Employ a thickness gauge (Peacock G-2.4 N OZAKI MFG. Co., Ltd., Tokyo, Japan) with a resolution of 0.01 mm to measure the thickness of EF at three randomly selected positions.

2.3.3. Moisture content

The moisture content measurement followed the manufacturer's standard operating procedures (SOPs). The sample's moisture content was measured using a digital moisture analyzer (Xy-105 MW, Shanghai Yanhe Instrument Equipment Co., Ltd., China) and reported as a percentage (%).

2.3.4. Moisture content and water activity (aw)

The moisture content and Aw measurements were performed according to the Official methods (934.01 and 978.18) described in AOAC (2023a, 2023b). The sample (5 g) was grounded and recorded, then dried to constant weight using a moisture meter, and recorded the dried weight. In addition, the sample (2 g) was weighed, ground, and placed in the digital Lab moisture analyzer (Xy-105 MW, Wincom Co. Ltd., Shanghai, China) to determine the Aw.

2.3.5. Solubility and swelling power (SP)

The solubility and SP of EFs were determined using the method employed by Huang, Chiu, Chan, et al. (2024), with minor modifications. The EF (4 cm^2) underwent a drying process using hot air at 80 °C until it reached a state of constant weight (W1). Next, the EF was immersed in DDW and left undisturbed at a temperature of 25 °C for 24 h prior to being measured weight. Afterward, it underwent a subsequent drying process until reaching a consistent weight (W2). The solubility was calculated using the provided Eq. (Eq).

$$\text{Solubility}\ (\%) = \frac{W1 - W2}{W1} \times 100 \quad (1)$$

The codes in Eq are shown in the above-mentioned steps.

The operations were conducted as mentioned earlier, except that the EF was immersed in DDW for 24 h and promptly removed. Afterward, the EF was dried using paper towels, and its weight was measured (W3), while the SP of EF was determined by employing the subsequent Eq:

$$\text{Swelling degree}\ (\%) = \frac{W1 - W3}{W1} \times 100 \quad (2)$$

The codes in Eq are shown in the above-mentioned steps.

2.3.6. Contact angle

The EF's contact angle was determined using a contact angle analyzer (Biolin Scientific AB, Gothenburg, Sweden) while adhering strictly to the manufacturer's SOPs. The surface of the EF was measured by applying 10 μL DDW onto three randomly selected locations on the EF.

2.3.7. Determination compositions of the functional groups

The sample's functional groups were determined following the procedure outlined by Huang, Wang, and Chang (2024) with slight

modifications. The 2 mg sample was combined with 120 mg of potassium bromide (KBr) and then compacted into a 13 mm film tablet utilizing a tablet press. Afterward, a Fourier transform infrared spectrometer (FT-IR, Satellite 5000, Mattson Technology, Fremont, CA, USA) was employed to perform scanning within the 400–4000 cm^{-1} range.

2.4. Measurement of mechanical properties of edible film (EF)

2.4.1. Tensile strength (TS)

The universal tensile testers (QC-501M2F, Chun Yen Testing Machines Co., Ltd., Taichung, Taiwan) were employed to determine the TS of EF specimens measuring 5 × 15 cm following the SOPs outlined in the manufacturer's manual. An external force was applied to EF until it reached its fracture point, at which the maximum TS of EF in kg-force (kgf) was recorded.

2.4.2. Elongation at break (EAB)

The EAB of EF was measured as described in section 2.4.1 above using a universal material tester. Briefly, a force was applied to a 3× 15 cm piece of EF until the EF broke, and then the ratio of the tensile length of the EF to the initial area was EAB expressed as a percentage (%).

2.5. Evaluation of the shelf-life preservation of cherry tomatoes (CT)

2.5.1. Sample preparation

The preparation of CT samples (EFs encapsulation and coating) was carried out according to the method described in Lee, Yu, Tsay, et al. (2024), and Yu et al. (2024) with minor modifications. The CTs were rinsed with tap water, dried, and immersed in a 0.05 % sodium hypochlorite solution for 3 min. They were randomly divided into three groups: control, film, and coating (n = 25). The Film group used EF covering for each CT, while the coating group applied 25 mL of spray coating for 3 min. Excess liquid was drained, and CTs were left to dry for 20 min at 25 ± 2 °C. All groups were packaged in corrugated cartons (23 × 14 × 13 cm) and stored at 20 ± 2 °C and 55–70 % RH. Nine CTs were sampled at each time point (0, 4, 8, 12, 16, 20, 30, and 40 days).

2.5.2. Determination of lycopene content

The lycopene content of the CT was determined using the methods outlined in Choudhary et al. (2009) with minor modifications. Briefly, a mixture was prepared by combining 0.6 g of CT with solvents consisting of 5 mL of a solution containing 0.05 % p-cresol hydroxyanisole acetate, 5 mL of 95 % ethanol, and 10 mL of hexane. The mixture was stirred in an ice bath at 180 rpm for 15 min, then 3 mL ice DDW was added, followed by another 5 min of stirring. The mixture stood at 25 °C for 5 min, then the absorbance of the upper layer was measured at 503 nm by UV–Vis spectrophotometer (UV-1500PC, Macylab Instruments, Shanghai, China). The lycopene content of the sample was calculated according to the following Eq:

$$\text{Lycopene content } (\mu g/g) = \left(\frac{X}{Y}\right) \times A503 \times 3.12 \quad (3)$$

where,

X represents the volume of hexane (mL), Y represents the weight of the fruit (g), A 503 represents the absorbance at 503 nm, and 3.12 represents the extinction coefficient.

2.5.3. Determination of ascorbic acid content

The determination of ascorbic acid in the sample was performed according to the protocol described by Lee, Yu, Tsay, et al. (2024). The sample, weighing 5 g, was introduced into a solution containing 50 mL of HPO_3 with a concentration of 3 %. The mixture was thoroughly blended and subsequently filtered. Next, a portion of the filtrate measuring 5 mL was combined with an equal volume of HPO_3 and subjected to titration using indophenol until the solution exhibited a pink coloration. As mentioned earlier, the procedure was repeated for the 1 mM ascorbic acid standard. The ascorbic acid content in CT was calculated using the Eq provided, expressed as mg/mL.

$$\text{Ascorbic acid content } (mg/mL) = \frac{\text{The volume of indophenol consumed} \times DF \times K}{5mL} \quad (4)$$

where,

DF indicates the dilution of the sample, and K indicates the mg of vitamin C in 1 mL of indophenol.

2.5.4. Determination of weight loss (WL)

The determination of WL was based on the methodology described by Yu et al. (2024). The weight of CT was weighed at 5-day intervals during storage, and WL calculations were performed using the following Eq:

$$\text{Weight loss rate } (\%) = \frac{\text{Initial weight} - \text{Weight after storage}}{\text{Initial weight}} \times 100 \quad (5)$$

2.5.5. Appearances and color analysis

The CT appearance and cross-section observation method was based on Huang et al. (2023). The CT appearance and cross-section microstructure were recorded photographically by observing the CT with a Stereo Microscope (Zeiss Stemi 2000-C, Edmund Optics Inc., Taichung, Taiwan). The differences in the appearance and cross-section of the CTs during storage were recorded using a 12.3-megapixel digital camera (Nikon D300, Nikon Corporation, Tokyo, Japan). The CTs were photographed in an environment with a 6500 k natural light source under the lens at a distance of 5.7 cm from the sample. In addition, the color analysis (a^* and b^* values) was the same description as in Section 2.3.1.

2.5.6. Titratable acidity (TA)

TA in CT was determined following the methodology described by Lin, Tsai, et al. (2023) with minor adjustments. The CT pulp (10 g) and 100 mL of DDW were for homogenization and filtration. Then, the supernatant was taken in 25 mL and titrated with 1 N NaOH to the endpoint of the titration. The TA content in CT was represented as citric acid, as calculated by the following Eq:

$$\text{Titratableacidity (TA; \%)} = \frac{\text{NaOH consumption (mL)} \times \text{Factor (F) of NaOH} \times 0.075 \times \text{dilution factor}}{10\ \text{(g)}} \times 100 \quad (6)$$

2.5.7. pH value

The pH was determined using the methods described by Lin et al. (2022) with minor modifications. The sample of SF was homogenized with sterile distilled water at a ratio of 1:1 (*v/v*) while using a portable meat pH meter (HI-99163, Hanna Instruments, Inc., Woonsocket, RI, USA) to determine pH value of each group.

2.5.8. Total soluble solids (TSS)

TSS was determined in CT pulp juice following the methodology outlined by Lee, Yu, Yen, et al. (2024). The CT's TSS was measured utilizing a handheld refractometer (N-1E, Atago Co., Ltd., Tokyo, Japan) and represented as °Brix.

2.5.9. Firmness and elasticity

The determination of CTs' firmness and elasticity was derived from the report by Lee, Yu, Tsay, et al. (2024), with slight modifications. Briefly, the texture analyzer (Brookfield CT3–4500, AMETEK. Inc., Berwyn, PA, USA) was utilized to measure the CT firmness and elasticity. The measurement conditions involved using a probe with a diameter of 4 cm and setting the probe distance at a depth of 10 mm. A single point on the equator of each fruit was selected for measurement. The average values were separately obtained for both the front and back sides of each fruit, while firmness was expressed in Newtons (N).

2.5.10. Decay rate of cherry tomatoes (CT)

Decay rate calculations were based on the approach described by Cheng et al. (2023). The CT was visually observed for decay by either physical injury or microbial pollution at sampling points during storage and was calculated using the following equation Eq:

$$\text{Decay rate (\%)} = \frac{\text{Number of fruits with decay}}{\text{Total number of fruits}} \times 100 \quad (7)$$

2.6. Statistical analysis

All experiments in this study were conducted with three replicates ($n = 3$). The statistical analyses used GraphPad Prism (Version 10.3.0 (461), Dotmatics, Boston, MA, USA). Within-group differences were assessed using *t*-tests, while between-group comparisons were conducted using the Tukey Multiple Comparison test. While the significance level of $p < 0.05$ indicated statistical significance.

3. Results and discussion

3.1. Effects of different composition ratios on the physicochemical and mechanical properties of edible film (EF) derived from water extracts of Premna microphylla Turcz leaf (PMWE)

3.1.1. Optimal ratio of edible film (EF)

This study showed that different ratios of PMWE (25–100 %) and glycerol (0–20 %) exhibited only a marginal effect on the thickness of EFs (Table 1), which showed no significant differences between groups. It is worth mentioning that the thickness of EF decreases marginally with increasing PMWE concentrations. It was hypothesized that the cross-linking between phenol-protein-polysaccharides reduces the interchain space of the EF polymer (Wei et al., 2024; Zioga et al., 2024). However, the EFs in this study were twice as thick compared to a previously published report EF (0.066 mm) of fish skin gelatin/guava leaf extract (Chou et al., 2023). The possible reasons were hypothesized to be the higher solid content in the PMWE substrates or the formation of the thicker structure by the adhesive linkage of polyphenols with the colloids, respectively (Chou et al., 2023; Liu et al., 2020). Notably, it has been shown that in electrostatic spraying, the droplets dispersed more thinly, resulting in a thinner coating film (0.0043 mm) for a shorter drying time, which saves on the cost of the coating process (raw materials and energy consumption for drying) (Wang et al., 2023). In addition, it has also been reported that plasticizers and lipid materials (emulsified substances) enhanced the film thickness following the incorporation of film-forming dispersants after drying (Behjati & Yazdanpanah, 2021). However, EF in the range of 0.050–0.250 mm flakes has been widely reported for packaging food products, namely bags, pouches, or gaskets between layers of food products, to avoid sticking (Abdillah et al., 2024).

3.1.2. Color analysis and appearance

This study's results showed a decreasing trend ($p < 0.05$) in the L^* values of EFs with increasing PMWE concentration (Table 1). However, no consistent pattern was observed in the changes of the a^* and b^* values despite significant differences between groups ($p < 0.05$). Specifically, the groups of EFs exhibited a progressive shift towards darker, greenish, and yellowish hues with increasing concentrations of PMWE, reflecting the same trend observed through visual inspection (Fig. 1). However, the color of EFs remained relatively stable despite increasing glycerol concentrations. It was proposed that the concentration of PMWE played a dominant role in determining the color change of EFs. It is worth noting that many studies of bioactive substances derived from plants have reported positive b^* values for EF, which are hypothesized to be related to pigments [e.g., phenolics or flavonoids (quercetin, luteolin, apigenin, etc.)] in the plant (Akay et al., 2024; Chen et al., 2023; Chou et al., 2023; Kolgesiz et al., 2023; Ngo et al., 2020; Zioga et al., 2024). It has been suggested that low-transparency EFs exhibit reduced light sensitivity for foods (Behjati & Yazdanpanah, 2021). However, to address the issue of transmittance and enhance visual observation of the color of food packaged inside, it is proposed that the homogeneity of various substances be improved and incorporated into the formulation of EF structure (Behjati & Yazdanpanah, 2021).

3.1.3. Moisture content and water activity (aw)

This study showed that compared to the 0 % PMWE group, the moisture content of EF increased following PMWE increasing in the formulation for all other groups (Table 1), whereas the opposite trend was observed for Aw, and there was a significant difference between the groups ($p < 0.05$). It was hypothesized that the interaction between phenolic substances present in PMWE and colloidal molecules via hydrogen bonding contributed to this phenomenon, attenuating the affinity between hydrophilic compounds of the colloid and water

Table 1
Effects of different formulations (including *Premna microphylla* Turcz leaf water extracts (PMWE), glycerol, 1.2 % carrageenan, and 0.6 % gelatin) on the physicochemical and mechanical properties of edible films.

Concentration (%)		Thickness (mm)	*L**	*a**	*b**	Moisture Content (%)	Water activity (Aw)	Solubility (%)	Swelling power (SP, %)	Elongation at break (EAB, %)	Tensile strength (TS) kgf
PMWE	Glycerol										
0		0.13 ± 0.01^{a}	16.90 ± 0.20^{d}	−0.69 ± 0.15^{b}	−1.90 ± 0.22^{a}	27.33 ± 0.03^{a}	0.46 ± 0.02^{c}	58.83 ± 0.03^{d}	509.09 ± 173.2^{b}	9.75 ± 0.34^{a}	50.72 ± 3.13^{a}
25		0.14 ± 0.03^{a}	15.36 ± 0.26^{c}	−1.56 ± 0.14^{c}	6.01 ± 0.21^{c}	30.27 ± 0.02^{b}	0.37 ± 0.03^{b}	22.52 ± 0.02^{a}	408.0.3 ± 41.12^{a}	9.05 ± 0.21^{a}	46.82 ± 5.16^{a}
50	0	0.13 ± 0.02^{a}	14.08 ± 0.23^{c}	0.6 ± 0.08^{b}	10.4 ± 0.27^{d}	37.35 ± 0.32^{e}	0.32 ± 0.01^{a}	27.32 ± 0.03^{c}	407.31 ± 45.04^{a}	9.70 ± 0.23^{a}	45.76 ± 8.03^{a}
75		0.12 ± 0.01^{a}	12.04 ± 0.05^{b}	−0.97 ± 0.24^{d}	10.1 ± 0.63^{b}	35.75 ± 0.23^{d}	0.31 ± 0.01^{a}	25.47 ± 0.23^{b}	407.02 ± 48.05^{a}	9.82 ± 0.11^{a}	49.10 ± 4.43^{a}
100		0.11 ± 0.01^{a}	11.77 ± 0.46^{a}	−0.15 ± 0.04^{a}	15.50 ± 0.23^{e}	32.71 ± 0.17^{c}	0.31 ± 0.02^{a}	26.66 ± 0.17^{b}	406.4 ± 37.23^{a}	9.73 ± 0.43^{a}	44.63 ± 5.37^{a}
	2.5	0.11 ± 0.01^{a}	7.14 ± 0.73^{a}	−0.45 ± 0.07^{d}	11.75 ± 0.12^{b}	29.72 ± 0.12^{a}	0.47 ± 0.03^{a}	52.14 ± 5.84^{d}	427.27 ± 76.73^{b}	5.43 ± 0.14^{a}	57.31 ± 0.27^{b}
	5	0.12 ± 0.02^{a}	8.91 ± 0.24^{a}	−0.33 ± 0.07^{c}	12.02 ± 0.08^{b}	32.38 ± 0.11^{a}	0.37 ± 0.01^{a}	27.12 ± 3.21^{b}	409.32 ± 72.01^{a}	7.68 ± 0.17^{a}	55.76 ± 0.15^{b}
75	10	0.14 ± 0.03^{a}	8.87 ± 0.35^{a}	−0.33 ± 0.09^{c}	10.97 ± 0.17^{a}	34.92 ± 0.12^{a}	0.41 ± 0.01^{a}	15.28 ± 2.33^{a}	407.14 ± 78.14^{a}	10.68 ± 3.21^{b}	45.76 ± 0.12^{a}
	15	0.14 ± 0.02^{a}	9.56 ± 0.27^{b}	−0.18 ± 0.02^{a}	10.10 ± 0.15^{a}	32.84 ± 0.34^{a}	0.42 ± 0.02^{a}	32.46 ± 3.42^{c}	412.5 ± 75.12^{a}	15.65 ± 2.16^{c}	42.10 ± 2.11^{a}
	20	0.13 ± 0.02^{a}	9.73 ± 0.51^{b}	−0.21 ± 0.01^{b}	10.73 ± 0.08^{a}	34.63 ± 0.25^{a}	0.46 ± 0.02^{a}	48.23 ± 3.13^{d}	418.75 ± 73.43^{a}	21.24 ± 3.23^{d}	38.67 ± 4.13^{a}

molecules and reducing moisture content (Liu et al., 2020; Wei et al., 2024; Zioga et al., 2024). In addition, the incorporation of glycerol in the formulation showed insignificant effects on the moisture content and Aw of the EF despite minor differences in the values from the control group (75 % PMWE with 0 % glycerol). However, the solubility decreased, followed by an increase upon adding glycerol to the formulation; notably, the 75 % PMWE with the 10 % glycerol group demonstrated significantly reduced solubility ($p < 0.05$). This phenomenon can be attributed to the gradual enhancement in EF's hydrophilicity beyond a certain threshold due to glycerol incorporation, resulting in increased solubility. Although there was a slight elevation in values, no statistical significance was observed for Aw. The potential explanation involves abundant hydrophilic groups (such as -OH) in gelatin and carrageenan, facilitating water retention within the EF structures (Wei et al., 2024).

3.1.4. Solubility and swelling power (SP)

This study showed that PMWE reduced EF solubility and SP, significantly different ($p < 0.05$) compared to the 0 % PMWE group (Table 1). Specifically, 25–100 % PMWE groups provided a 50 % reduction in solubility and a 20 % reduction in SP compared to the 0 % PMWE group. However, the EF formulation incorporating glycerol exhibited a significant decrease followed by an increase. Notably, 10 % glycerol demonstrated the lowest solubility ($p < 0.05$), which implies a tighter structural composition and better resistance to the water solubility of this EF group (Wei et al., 2024). In addition, high-solubility films may promote the release of biologically active substances from the film (Chou et al., 2023). In contrast, despite a slight increase, no statistically significant difference was observed for SP. This observed phenomenon can be ascribed to the incorporation of glycerol above a certain threshold, which gradually enhances the hydrophilicity of the EF and consequently increases its solubility.

3.1.5. Elongation at break (EAB) and tensile strength (TS)

The TS value of EF increased, and the EAB value decreased, necessitating EF's mechanical reinforcement and extensibility enhancement to withstand external stresses while preserving its integrity and barrier properties (Arcan & Yemenicioğlu, 2011; Rashid et al., 2024; Zioga et al., 2024). Consequently, incorporating hydrophilic moieties derived from phenolic compounds has been frequently employed to modulate the hydrophobic interactions among EF molecules, enhancing their fluidity and addressing EFs' brittleness and flexibility (Arcan & Yemenicioğlu, 2011; Rashid et al., 2024; Zioga et al., 2024).

This study's results showed no significant differences in EAB and TS for EFs with different ratios of PMWE (Table 1) despite minor differences in the values compared to the 0 % PMWE group. Conversely, the EAB of EF exhibited a gradual increase, whereas the TS of EF demonstrated a gradual decrease ($p < 0.05$) with an increasing proportion of glycerol incorporated in the EF formulation. Notably, the mechanical properties of EFs involved thickness, while they were characterized by more excellent resistance to EAB associated with a high TS that required more robust strength to be fractured (Behjati & Yazdanpanah, 2021; Chou et al., 2023), consistent with the thickness results described above. However, the results of this study revealed that PMWE incorporation appeared infrequently to be the primary factor affecting the mechanical properties of EFs; rather, these properties depended more on the glycerol percentage. It has also been reported that such changes may be attributed to the hydrogen bonding interactions of the samples, which consequently affect the TS of the EFs (Abdillah & Charles, 2021; Liu et al., 2020). In particular, hydrogen bonding has been observed to occur via the interaction between hydroxyl groups of phenolic compounds and various other functional groups, such as glycosidic linkages, carbonyl and carboxylic acid groups, and oxygen atoms (Büyük et al., 2024). Jiang et al. (2024) also reported that bioactive substances incorporated into the formulation might potentially bridge the pores in the structure of the composite colloidal network, thereby enhancing the film's mechanical properties. However, the molecular size of the plasticizer has

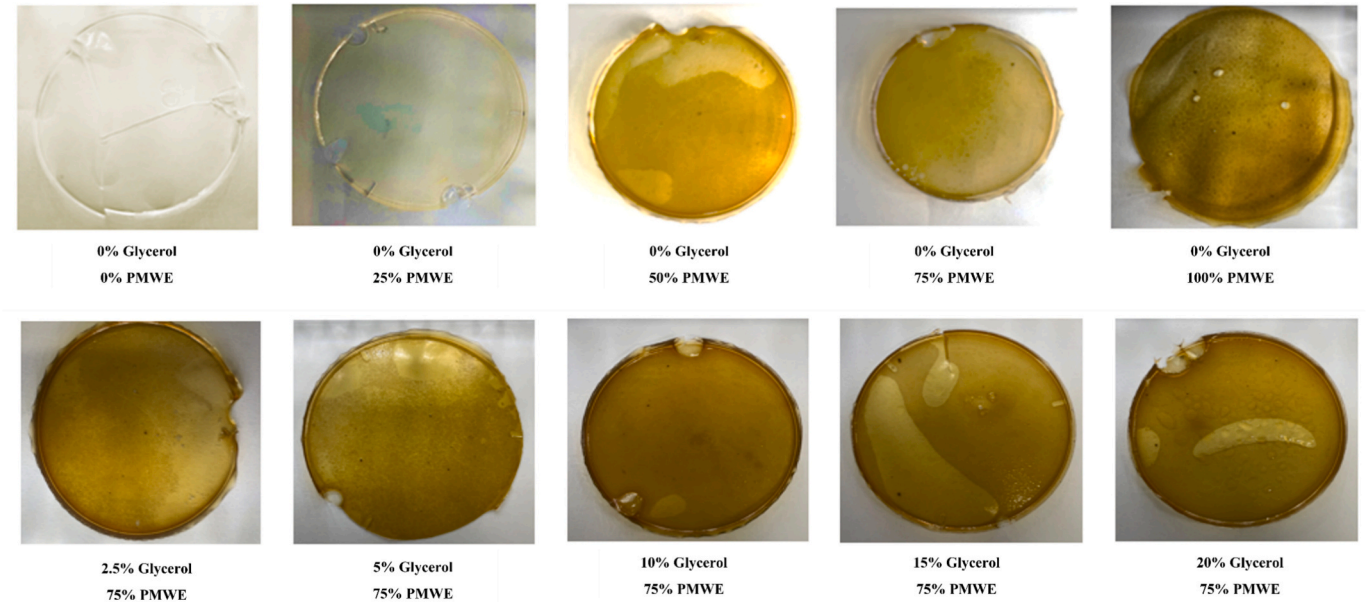

Fig. 1. Effects of various formulation compositions [containing 0–100 % *Premna microphylla* Turcz leaf water extracts (PMWE) and 0–20 % glycerol] on the visual aesthetics of edible films (EFs).

also been reported to affect the tensile performance of EFs, and in particular, the small molecule plasticizer (glycerol) tends to diffuse more readily into the polymer chain by disrupting the hydrogen-bonding interactions (Dang & Yoksan, 2021). Conversely, the large molecule plasticizers sorbitol, xylitol, etc.) have fewer effects. The cyclic molecular structure of phenol has been reported to impede the bonding of

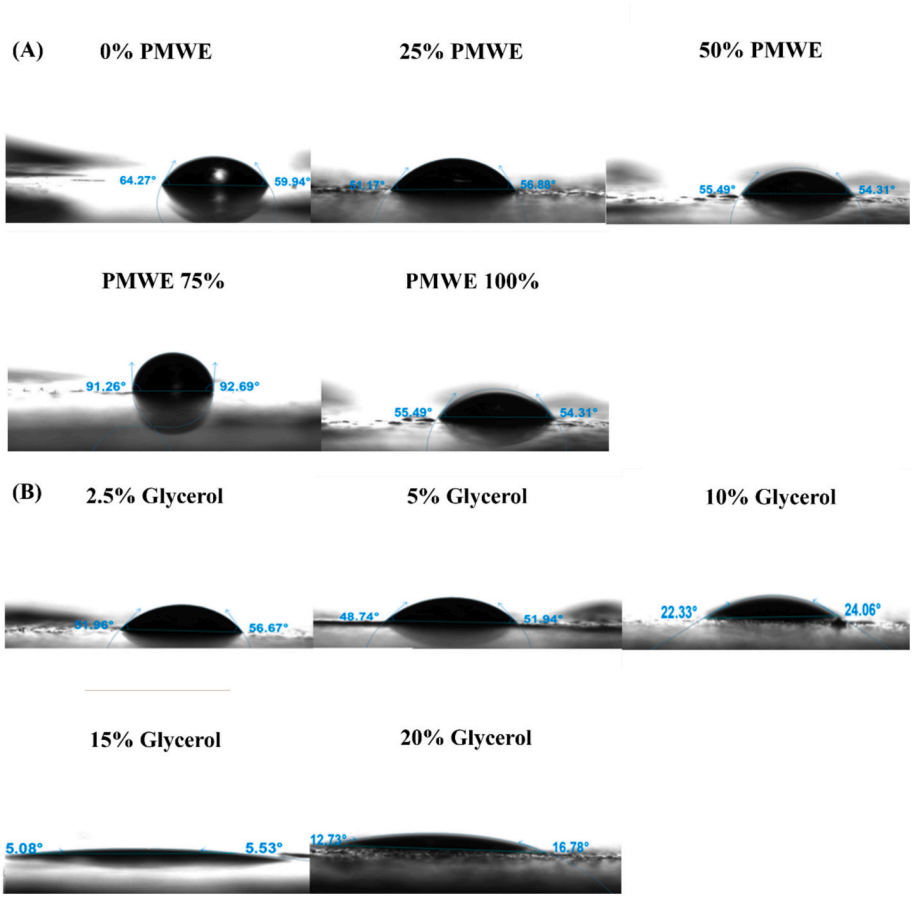

Fig. 2. Effects of different formulation compositions [containing 0–100 % *Premna microphylla* Turcz leaf water extracts (PMWE) and 0–20 % glycerin] on the contact angle of edible films (EFs). (A) different *Premna microphylla* Turcz leaves water extract (PMWE) concentrations, (B) 75 % PMWW with different glycerol concentrations.

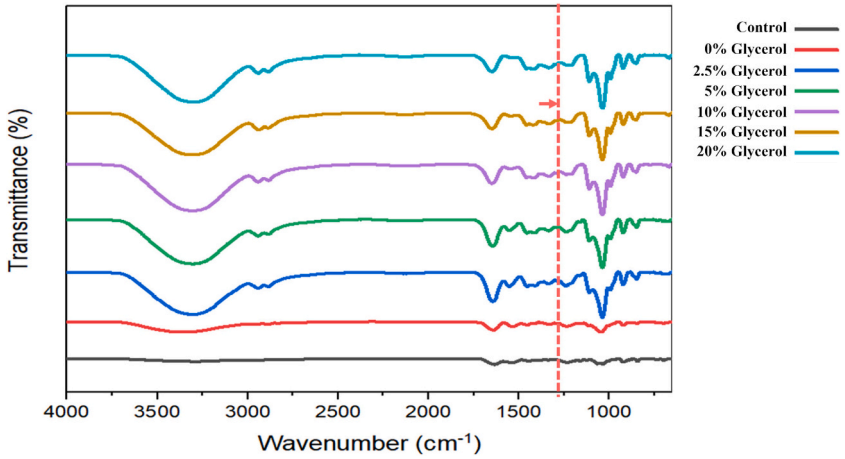

Fig. 3. Effects of different formulation compositions [containing 75 % *Premna microphylla* Turcz leaf water extracts (PMWE) and 0–20 % glycerin] on the compositions of the functional groups of edible films (EFs). Control: EFs without PMWE and glycerol; 0–20 % glycerol: EFs with 75 % PMWE and 0–20 % glycerol.

rotating EFs freely, thereby counteracting the impact of plasticizers and influencing mechanical performance (Wei et al., 2024). Meanwhile, enhancing the EFs' structure through nano-treatment of relevant raw materials has been possible (Wei et al., 2024).

3.1.6. Contact angle

The efficiency of the water barrier can commonly be evaluated based on the contact angle, where a contact angle below 75° indicates a surface easily wetted and exhibits high hydrophilicity (Fatima et al., 2024). Conversely, an intermediate wetting is observed for contact angles between 75 and 105°, while a contact angle greater than 120° signifies enhanced hydrophobicity towards non-aqueous liquid wetting (Fatima et al., 2024).

The control group (0 % PMWE) exhibited a flat shape due to its hydrophobicity (Fig. 2A). However, with an increase in PMWE concentrations, the contact angle showed a slight increment, which was

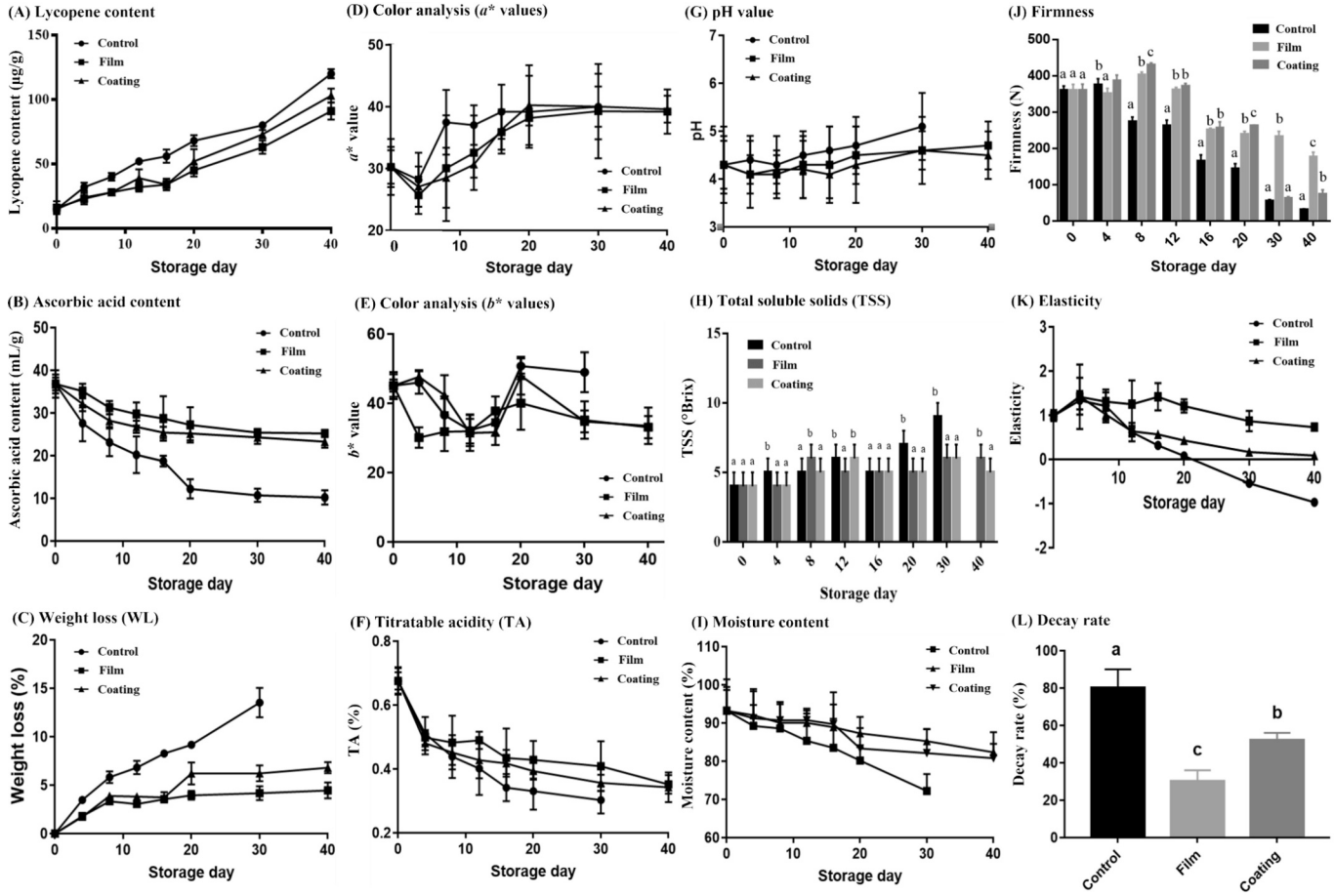

Fig. 4. Effects of edible films (EFs) and coating prepared from water extracts of *Premna microphylla* Turcz's leaf (PMWE) on the quality indicators of cherry tomatoes (CTs) during shelf-life preservation: (A) lycopene content, (B) ascorbic acid content, (C) weight loss, (D) color analysis (*a** values), (E) color analysis (b* values), (F) titratable acidity (TA), (G) pH value, (H) total soluble solids (TSS), (I) moisture content, (J) firmness, (K)elasticity, and (L) decay rate.

maximum in the 75 % PMWE group (91.26 and 92.96°). The mechanism of this phenomenon was reported that the phenolics in PMWE weakened the interaction between hydrophilic groups and water molecules in the composites through hydrogen bonding (Wei et al., 2024; Zioga et al., 2024). It was hypothesized that specific chemical components present in the PMWE could interact with the material components within the EF, leading to structural (arrangement) or surface properties alterations. Consequently, these reactions or interactions may induce a transition of the EF from hydrophilicity to hydrophobicity, thereby influencing the contact angle (Behjati & Yazdanpanah, 2021; Rashid et al., 2024). In this study, the results indicate that EF's contact angle exhibited a negative correlation with the glycerol concentration. It has been reported ascribed to an augmentation in the quantity of hydrophilic OH functional groups on the surface of EF. It also indicates an expansion in the matrix's free volume (Dang & Yoksan, 2021). Moreover, it has been reported that the molecular size of the plasticizer increases the EF wettability or decreases the surface hydrophobicity; specifically, there has been a negative correlation between the angle of contact and the molecular size and concentration of the plasticizer (Dang & Yoksan, 2021). Based on the above results, the formulations used in this study incorporating glycerol provided hydrophilicity to the EFs, implying that the coating could form a washable film directly on the food surface (Li et al., 2023).

3.1.7. Compositions of the functional groups

This study showed that all the EFs containing 75 % PMWE with various concentrations of glycerol (Fig. 3) exhibited the changes observed in the following board peak ranges: the spectral peaks observed within the 3600–3000 cm^{-1} range correspond to the presence of hydroxyl (OH) groups in carboxylic acid and unbound OH stretching bonds (Behjati & Yazdanpanah, 2021; Lin et al., 2024; Wei et al., 2024). The 2885–2935 cm^{-1} corresponded to the stretching of the C—H of anhydrous glucose rings (-CH_2) contraction of gelatin or carrageenan (Huang, Chiu, Lu, et al., 2024; Jiang et al., 2024; Lin et al., 2024). In addition, the heightened intensity of the bands within each PMWE group, compared to the control group, can be ascribed to the hydrogen bonding interactions among the components. These interactions align with the heightened mechanical properties of EFs (as Section 3.1.5). The belt peaks at 1540–1750 cm^{-1} indicate the presence of moisture molecules in the EFs (Fatima et al., 2024). The belt peak ranges 1630–1657 cm^{-1} corresponds to amide (C=O) and C=N stretching (Abdillah et al., 2024; Chou et al., 2023; Fatima et al., 2024; Jiang et al., 2024), while 1240–1451 cm^{-1} corresponds to the ester sulfate group (O=S=O) (Abdillah et al., 2024; Liu et al., 2020). Notably, the primary change in the PMWE formulation incorporating glycerol showed up at 1500–1700 cm^{-1}, corresponding to the interaction of glycerol with the amino group on the carrageenan and the carboxyl group (COOH) on the gelatin (Huang, Chiu, Lu, et al., 2024; Ngo et al., 2020). Specifically, the vibration belt of the amino group at 1544 shifts to 1419 cm^{-1}; namely, while the peak strength and arrangement alterations resulted from forming hydrogen bonds within the EF due to carrageenan chains, glycerol, and phenols of PMWE (Kolgesiz et al., 2023; Liu et al., 2020). It has also been reported that the positively charged oxygen in the ring molecules of phenolic substances interacts with the negatively charged sulfate esters of the carrageenan chains to form hydrogen bonds by electrostatic interactions (Kolgesiz et al., 2023; Liu et al., 2020; Zepon et al., 2019). In addition, 1066–1040 cm^{-1} corresponds to the stretching vibrations exhibited by glycosidic bonds (Behjati & Yazdanpanah, 2021), attributed to the interaction of OH groups of glycerin and gelatin (Dang & Yoksan, 2021). However, It has been documented that the spectral bands within the range of 915–958 cm^{-1}, attributed to 3,6-anhydrogalactose, and 842–849 cm^{-1}, attributed to galactose-4-sulfate were indicatively linked to carrageenan and glycerol components (Abdillah et al., 2024; Abdillah & Charles, 2021; Dang & Yoksan, 2021; Sedayu et al., 2021). According to the above results, there were no significant differences in the physicochemical properties of the EFs, such as thickness, color, contact angle, and functional group composition. Therefore, the EF formulation of 75 % PMWE and 5 % glycerol was chosen to provide the best EAB performance despite the slightly greater solubility than that of 75 % PMWE with 10 % glycerol, considering the premise of maintaining the moisture content and stability effectively. Thus, this formulation (as described in Section 2.2) was subsequently used to evaluate the shelf-life preservation of the CTs.

3.2. Effects of edible film (EF) and coating prepared from water extracts of Premna microphylla Turcz leaf (PMWE) on the quality indicators of cherry tomatoes (CTs) during shelf-life preservation

3.2.1. Lycopene content

Lycopene, a carotenoid compound, is known to play a pivotal role in the process of tomato ripening. The accumulation of carotenoids experiences a rapid surge during the turning-to-light-red stages of tomato harvesting, culminating in the highest levels of lycopene observed in tomatoes harvested during the red stages (Alenazi et al., 2020).

This study showed that the lycopene content of each group increased following the storage period (Fig. 4A). Specifically, the control group increased more than the film and coating groups. It was hypothesized that the film and coating inhibited the respiration of CTs, thereby delaying the ripening process. Moreover, the application of relevant edible coatings has been extensively employed to confer advantageous effects by suppressing ethylene biosynthesis in postharvest fruits, concurrently reducing respiration rates and impeding respiratory metabolism through oxygen content reduction (Lee, Yu, Tsay, et al., 2024; Yu et al., 2024). Specifically, the film and coating serve as a protective barrier, effectively mitigating the oxygen flow (i.e., the exchange of gases between the fruit and its surrounding environment), thereby inducing delayed fruit metabolism throughout its shelf-life (Lee, Yu, Tsay, et al., 2024).

3.2.2. Ascorbic acid content

This study showed that the ascorbic acid content of CTs decreased gradually with time in all groups during 40 days of storage (Fig. 4B). Notably, the film and coating groups decreased less than the control group. The observed phenomenon was ascribed to the association of films or coatings with impeding gas exchange between the CTs and the external environment during storage, thereby restricting respiration (Lu et al., 2023). Furthermore, ascorbic acid has been identified as a prominent constituent of the plant defense system with potent antioxidant properties. During fruit ripening, an upsurge in oxygen radicals (reactive oxygen species) occurs due to respiration, leading to oxidation and subsequent decline in ascorbic acid content (Ranjith et al., 2022; Zhao et al., 2023). The levels of ascorbic acid, citric acid, oxalic acid, and malic acid in fruits are known to exhibit an increase during the process of ripening (Huang, Cheng, et al., 2024). However, once tomatoes are harvested, there is no further accumulation of ascorbic acid content (Alenazi et al., 2020). Subsequently, enzymatic reactions occur, leading to vitamin C degradation as the pulp transition from soft to decayed. In particular, ascorbic acid serves as an indispensable cofactor for numerous enzymes involved in plant metabolism, including 1-aminocyclopropane-1-carboxylic acid oxidase, which plays a pivotal role in the final step of converting 1-aminocyclopropane-1-carboxylic acid into ethylene (Almeida et al., 2024; Yu et al., 2024). The reduction in O_2 levels from storing mangoes in a refrigerated environment with a modified atmosphere led to decreased ethylene synthesis and increased vitamin C accumulation (Lu et al., 2023). Therefore, maintaining an appropriate level of ascorbic acid through various techniques during the fruit storage period can effectively mitigate oxidative reactions that compromise commodities quality and reduce shelf-life (Yu et al., 2024).

3.2.3. Weight loss (WL)

This study showed that the control group WL exhibited a linear increase from day 4–20 of storage (Fig. 4C). It has been reported that a

positive correlation existed between the respiration rate of fruits (control group) during their shelf-life period and their WL (Lee, Wei et al., 2024; Ranjith et al., 2022; Yu et al., 2024), which agreed with this study's results. This also indicated that CT was accompanied by decreased moisture and nutrient contents during storage, which reduced CT's weight (Wang et al., 2023). Conversely, the film and coating groups showed a linear increase in the initial 4–8 days, followed by a plateau in the 8–20 days relative to the control group. Then, a slight increase was observed in days 20–40, which were significantly lower than the control group ($p < 0.05$). This phenomenon corresponds to the mechanism of decreasing respiration, reduced moisture loss, and nutrient depletion (Ruelas-Chacon et al., 2017; Wang et al., 2023), as stated above, while the specific changes in moisture content are discussed below (Section 3.2.8). Intriguingly, in this study, the trend of WL change in the initial 12 days of storage was similar compared to the WL change in the high-voltage electrostatic fields-treated CTs, whereas the high-voltage electrostatic fields-treated exhibited a substantial increase in WL starting on day 9 (Chang et al., 2023). On the 20th day of storage, the film and coating groups revealed a substantial difference in WL compared to the control group. This may be attributed to the CTs in the control group ripening at that time. In contrast, the film and coating groups effectively prolong shelf-life by minimizing the respiration of the CTs and prolonging the physiological phenomenon of ripening.

3.2.4. Color analysis (a* and b* values)

This study showed that the a^* value of each group decreased and increased with storage time and then stabilized (Fig. 4D). The b^* value decreased, followed by an increase in the film group during the initial 4–8 days (Fig. 4E). In contrast, the coating and control groups displayed a slight increase followed by a decrease. This trend persisted across all three groups until the 12 to 20th day, wherein an increasing pattern was observed with subsequent slight reductions until the end of the storage period. These phenomena were attributed to changes in the pigmentation of CT during the post-ripening process, namely increasing levels of lycopene and carotenoids, which caused a gradual reddish and slightly yellowish color. Several studies have also reported that different coating treatments suppressed ethylene production by modulating the respiration rate of the fruit while inhibiting chlorophyllase activity, thereby facilitating the preservation of fruit color during the shelf-life period (Lee, Yu, Tsay, et al., 2024; Ranjith et al., 2022; Yu et al., 2024). Meanwhile, pigments in films or coatings contain antimicrobial substances or bioactive compounds that reduce the clarity of these materials and influence the color properties of the encapsulated fruit (Ranjith et al., 2022). No migration of these compounds would affect the change in fruit color properties (Ranjith et al., 2022). Therefore, the respiration rate of the CT during post-ripening was influenced by either the film or the coating, leading to alterations in the atmospheric conditions and subsequently causing a delay in the appearance of color change (Ruelas-Chacon et al., 2017).

3.2.5. Titratable acidity (TA)

This study showed that the TA content of each group decreased following the increase in storage time (Fig. 4F). In particular, the control group was the lowest, while no significant difference between the film and coating groups was observed. Unfortunately, the TA content of the control group was undetectable on the 30th storage day. These phenomena were presumably attributed to both the covering and coating groups, which hindered the respiration pathway for CTs during the shelf-life and delayed the post-ripening process. The energy metabolic pathways, such as the fruit tricarboxylic acid cycle or amino acid deamidation, play an essential role in this phase (Ali et al., 2022; Lee, Yu, Tsay, et al., 2024).

3.2.6. pH value

This study showed that both groups of CTs, covering and coating, exhibited significantly lower pH than the control group during shelf-life ($p < 0.05$) (Fig. 4G), which trend exhibited a negative correlation with the TA content mentioned above (Akay et al., 2024). The pH of CT increases during storage, primarily due to the utilization of organic acids as substrates for respiration during ripening to maintain low acidity values (Zhao et al., 2023). This observation also suggests the formation of a film or coating on the surface of fruits, which establishes a barrier and consequently reduces the availability of oxygen required for respiration during storage, resulting in diminished metabolic activity (Akay et al., 2024). Moreover, the alteration of pH indirectly indicates the deterioration in the quality of CTs, specifically indicating a decline in freshness. Nevertheless, applying a covering or coating comprising PMWE can effectively inhibit the increase in the pH value of CTs.

3.2.7. Total soluble solids (TSS)

This study showed that the TSS during the storage period exhibited slight variations (Fig. 4H); in particular, the control group increased slightly on the 12th storage day, followed by an increase in the trend for 20–30 days ($p < 0.05$). In addition, the trend was correlated with the TA changes; specifically, the respiration process of fruits leads to the decomposition of macromolecular substances into smaller ones, resulting in an increase in TSS with storage time and subsequently leading to an elevation in TA (Ali et al., 2022; Lee, Yu, Yen, et al., 2024). Another plausible explanation could be that the CTs entered the post-ripening stage after harvest, during which starch underwent hydrolysis into soluble sugars, thereby contributing to increased TSS content (Zhao et al., 2023). However, following the progression of physiological activities, part of the TSS content declined rapidly due to the metabolic decomposition of the TSS (Zhao et al., 2023). It has also been reported that the TSS content of uncoated tomatoes was higher than that of coated ones, where the coating could form a film on the fruit surface, which contributed to the alteration of the internal atmosphere of the fruits (Nawab et al., 2017). Namely, increasing the CO_2 levels and decreasing the O_2 levels by modulating the respiration rate of the fruits, thus inhibiting the formation of ethylene, causing delayed ripening, resulting in the slower increase of TSS in the coated fruits (Nawab et al., 2017). It is worth mentioning that Wang et al. (2023) reported that the application of the coating by immersion facilitated the formulation as a uniform film on the fruit surface, providing a better oxygen barrier efficacy. The same authors also demonstrated that the approach mitigated mango respiration and nutrient consumption while delaying the reduction of the TSS. However, this study showed that the variations in TSS content for both film and coated groups were similar from the 0–30th storage period, and there was a slight difference for both groups and statistically significant until the 40th day ($p < 0.05$). Therefore, the findings of this study demonstrated that both PMWE film and coating could reduce respiration rate and ripening process in CT then, inhibiting sucrose hydrolysis into reducing sugar and slowing down TSS increase, while this phenomenon may vary depending on fruit variations (Rashid et al., 2024).

3.2.8. Moisture content

This study showed a negative correlation between moisture content and shelf-life for all groups (Fig. 4I), where the control group exhibited the most drastic decreasing trend compared to the other groups. The results suggest that the control group CT, lacking additional protective measures, exhibited greater susceptibility to storage processes, resulting in subsequent moisture loss. Reversely, the moisture contents of the film and coating groups exhibited a gradual decrease during the initial 16 days, with noticeable variations observed until the 30th day. Notably, it was found that the film group demonstrated superior performance in maintaining moisture content. This phenomenon was explained above by the protection provided by the film or coating against external contact, which mitigates moisture loss (Wang et al., 2023). Namely, the protection facilitates the reduction of evaporation and respiration of CT moisture, thus maintaining a relatively stable moisture content. Moreover, the post-harvest fruit remained a viable organism with ongoing

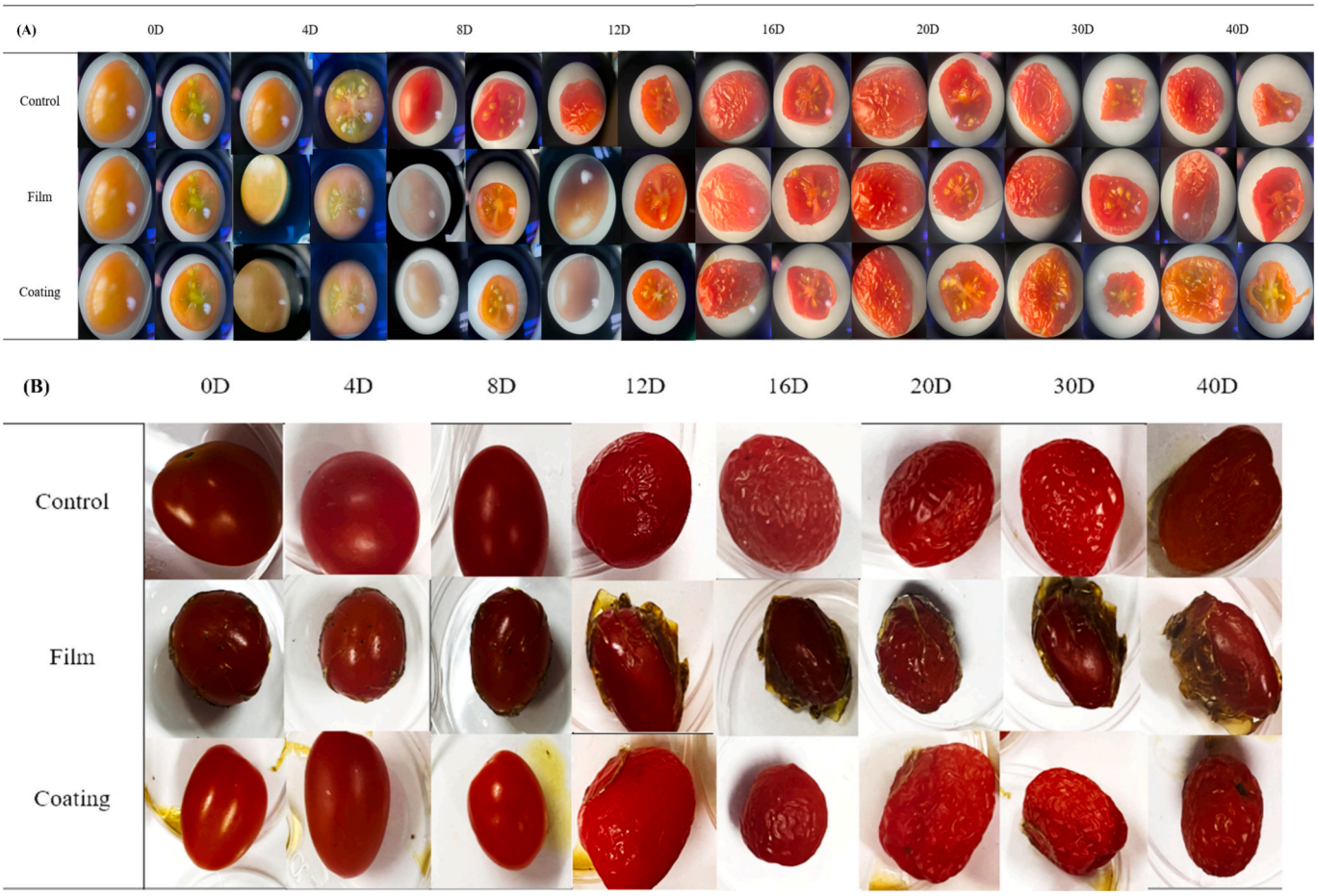

Fig. 5. Effects of edible films (EFs) and coating prepared from water extracts of *Premna microphylla* Turcz's leaf (PMWE) on the (A) appearance and cross-section (at stereo microscope) and (B) the appearance of cherry tomatoes (CTs) during shelf-life.

respiratory metabolism throughout its shelf-life period, depleting organic matter within the fruit and resulting in irreplaceable water loss through evaporation (Wang et al., 2023). Therefore, either edible films or coatings serve to minimize the weight loss of CTs due to water loss during storage while extending their shelf-life, which was beneficial for vegetables and fruits, similar to the previously reported results (Abdillah & Charles, 2021; Lee, Yu, Tsay, et al., 2024; Rather et al., 2022; Ruelas-Chacon et al., 2017; Tilahun et al., 2019; Zioga et al., 2024).

3.2.9. *Firmness and elasticity*

This study revealed a significant difference ($p < 0.05$) in firmness between control, film, and coated groups from the 8th day of storage (Fig. 4J). The potential explanation may be attributed to the normal respiration of CT in the control group, transitioning from the stage of color change to maturation. In contrast, the firmness of the film and coating groups declined gradually until the 16th day of storage, with a sharp decline compared to the firmness of the 0–12 days period. Subsequently, there was a slow decline until the end of the storage period, yet the firmness of the coated group was close to the control group's firmness value during the 30–40th days of storage. Simultaneously, as fruits undergo ripening and senescence, the reduction in firmness can be attributed to a decrease in cell expansion pressure and loss of cell wall relaxation (Huang, Cheng, et al., 2024; Lee, Yu, Yen, et al., 2024). Moreover, the elasticity showed the same trend as the firmness. This also indicates that the performance of the film group maintained CT firmness and elasticity better than the coating group. These phenomena relate to the softening of the fruit during the ripening process involving endogenous enzymes (pectinesterase (PE), polygalacturonase (PG), amylase, cellulase, etc.) hydrolyzing cell wall substrates (pectin, starch, cellulose, hemicellulose, etc.), thus causing structural changes and a decrease in firmness (Lee, Yu, Tsay, et al., 2024; Lu et al., 2023; Thompson et al., 2019; Wu et al., 2007; Yu et al., 2024). Notably, it has been reported that high-voltage electrostatic fields can indirectly attenuate the endogenous enzyme activities above rather than completely blocking them, and achieving complete inhibition necessitates excessive electric field effects (Chang et al., 2023). The same authors also reported that applying electric field treatment synergized with modified atmosphere packaging effectively regulates the respiration rate of fruits during storage, thereby enhancing storage benefits. Therefore, the use of films or coatings on CTs effectively mitigates the high levels of CO_2 by limiting the activities of the enzymes mentioned above, thereby maintaining the firmness and elasticity of the CTs during the shelf-life (Ruelas-Chacon et al., 2017).

3.2.10. *Decay rate, appearance, and cross-section*

This study showed that CT treated with EF film and coating with EFs for 40 days exhibited about 80 % decay in the control group, whereas 36 and 52 % in the film and coating groups, respectively ($p < 0.05$) (Fig. 4L). However, the preservation of film-covered CTs exhibited superior shelf-life due to the inhibitory effects of EF on the decay rate of CTs by effectively blocking the ingress of oxygen and moisture. Another potential explanation could be attributed to the formulations utilized in the film and coating groups, which contained 75 % PMWE and exhibited a high concentration of bioactive constituents such as phenolic compounds or flavonoids. Apart from components with antioxidant properties, they also confer a certain level of defense against microbiological infections.

Moreover, there was no evidence of decay in the initial 0–12th day of storage for both film and coated groups of CTs. In contrast, the control group exhibited decay beginning on days 8–12th of storage. However, regarding the appearance and cross-sectional alterations, the CT surface skin of all groups appeared to be wrinkled (Fig. 5 A and B), namely, dehydrated from the 12th day of storage, which continued to deteriorate until the end of the shelf-life trial. These trends were consistent with Abdillah et al. (2024) report of appearance changes in sweet cherries treated with arrowroot starch-carrageenan film, which was also consistent with the trend of WL changes described above. In addition, Lin et al. (2024) also reported the use of chicken protein-sodium alginate-sodium lignosulfonate nanoparticle films to prolong the shelf-life of fresh tomatoes for at least 8 days with observed quality degradation, which trends similar to this study. Specifically, during the post-ripening stage, protopectin, a widely distributed plant-insoluble pectin substance crucial for fruit texture, undergoes hydrolysis by PE and transforms into water-soluble pectin, reducing fruit firmness (Ali et al., 2022; Lee, Yu, Tsay, et al., 2024; Lee, Yu, Yen, et al., 2024; Thompson et al., 2019). Subsequently, PG affects the integrity of the middle cell layer rather than the fruit texture by degrading the pectin structure (Ali et al., 2022; Lee, Yu, Tsay, et al., 2024), which corresponds with the cross-section results of this study. Based on these results, this study's treatments of films and coatings can provide at least 4–8 days extra shelf-life compared to the control group; namely, the shelf-life ranges from 12 to 16 days. Unfortunately, the CTs in this study exhibited more pronounced wrinkling compared to the high-voltage electrostatic field-treated CTs (Chang et al., 2023). Despite the continuous shelf-life, CT surface wrinkles, and loss of commercial value, it maintains a specific quality profile and may be used as raw material for processing purposes. In addition, the PMWE film or coating effectively maintains the internal structural integrity of the CT, thus slowing down its ripening and aging process. This also presents a potential opportunity for enhancing the subsequent processing value of the CT. Hence, this study's results revealed that the EF formulation of 75 % PMWE with 5 % glycerol was probably used as a potentially effective preservation practice that could facilitate the extension of CT shelf-life and decrease the decay rate.

4. Conclusions

This study showed that 75 % of PMWE films and coatings combined with carrageenan (1.2 %) and gelatin (0.6 %) were successful in achieving the benefits of maintaining the CTs' quality indexes and extending the shelf-life of at least 4–5 days (compared to the control group). This achievement was attributed to effectively minimizing respiration and gas exchange rates of CTs. Unfortunately, despite substantially lower decay rates of CTs in the film and coating groups compared to the control group, the appearance of CTs started to exhibit wrinkling from the 16th day of storage onwards, severely compromising their visual appeal and market value. This study was conducted on a pilot scale, and here is an opportunity to address the identified limitations by improving the formulation of EF, potentially through synergistic effects with other effective methods (e.g., electric field, cold plasma, or others). In addition, a more profound enhancement of the water vapor transport properties in EF formulations is imperative to address the defective disordered color change observed in both film and coating groups of CTs during the 4 to 12th day of storage. This direction holds significant potential for future research endeavors. Therefore, this study's results provide opportunities for potential advances in the storage, shipping, and marketing of CTs. Implementing PMWE's complexes EF formulation enables the mitigation of food waste and the extension of the shelf-life and quality of highly perishable agricultural products.

CRediT authorship contribution statement

Ping-Hsiu Huang: Writing – original draft, Methodology, Formal analysis. **Cen-Hao Jian:** Validation, Methodology, Data curation. **Yu-Wen Lin:** Visualization, Formal analysis, Conceptualization. **Da-Wei Huang:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Funding acquisition, Conceptualization.

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.

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Data availability

Data will be made available on request.

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