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Water Vapour Permeability and Light-Barrier Properties of Starch Films Incorporated with *Amaranthus dubius* Extract for Potential Fruit Preservation

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ABSTRACT

Commercial fruit coatings such as beeswax and paraffin often cause problems such as poor gas exchange, blushing during storage, and skin whitening, limiting their effectiveness in maintaining fruit quality. Thus Amaranthus dubius (red spinach) having antioxidant and antimicrobial properties offers a promising solution. This study evaluated the effect of red spinach extract concentrations (40%, 60%, and 80% w/w polymer) on the light barrier and water vapor permeability (WVP) of starch films potential for fruit coating applications. Light barrier properties were evaluated by measuring film transmission at 200–800 nm using a UV–Vis spectrophotometer, while water vapour permeability was determined by the gravimetric cup method under controlled temperature and relative humidity. Light barrier analysis revealed a significant reduction in film transmission with 80% extract concentration, particularly at shorter wavelengths (200 nm), due to the high betacyanin content which absorbs and scatters light in the UV-visible spectrum. This suggests the films' potential as UV-blocking agents. Meanwhile, the WVP of all films decreased over a 7-day period. On day 1, the 60% extract film exhibited the highest WVP (1.88×10^{-6} g/d·m·Pa), attributed to hydrophilic compounds like betacyanin and polyphenols that enhance water vapor diffusion. However, as films dried, permeability decreased significantly, with the 40% extract film achieving the lowest value by day 7 (6.39×10^{-7} g/d·m·Pa), indicating greater structural compactness and barrier efficiency. Notably, the WVP values observed in this study were lower than the standard range for food packaging films, confirming the red spinach extract's contribution to improve moisture and UV barrier properties. These findings highlight the multifunctional potential of red spinach extract in edible coatings for extending shelf life and preserving the quality of fresh produce.

Keywords: Red spinach, Transparency, Water vapour permeability (WVP), Betacyanin, Edible film coating

1. INTRODUCTION

Coating fruit before shipping and marketing is an important postharvest step commonly practiced to improve visual appearance and prolong shelf life. Shellac, carnauba wax, beeswax, and paraffin wax are popular commercial coatings for various fruits to improve its fruit gloss, control water loss, and maintain the fruit quality through delayed ripening and senescence. However, those materials have inherent problems including poor gas permeability, blushing, and skin whitening during cold storage conditions (Khedr & Khedr, 2025) leading to unsuccessful postharvest ripening and finally destroying the fruit quality. To overcome these constraints, attention has shifted toward natural, edible, and biodegradable alternatives originated from plant sources, which can provide functional bioactive compounds in addition to acting as protective barriers.

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Red spinach (*Amaranthus dubius*), offers promising potential coating agent to enhance shelf life, improve light and water barrier properties, and preserve the sensory appeal of fruits during storage and distribution. This leafy vegetable in deep red color is linked to the high content of betacyanin. The specific betacyanin found in red spinach is amaranthine that is classified as a glycosylated betacyanin, composed of betanidin 5-O-β-glucuronosylglucoside that exhibits antimicrobial effects against both Gram-positive and Gram-negative strains of bacteria (Yong et al., 2017). Thus betacyanin are bioactive compounds that not only provide attractive coloration but also exhibit antioxidant and antimicrobial properties, contributing to improved food quality and potential health benefits. Utilizing red spinach as a natural colorant aligns with the shift toward sustainable and health-conscious food ingredients.

Edible films made from starch are a promising class of environmentally friendly coating materials that take advantage of the unique properties of starch to form thin, flexible films capable of encasing and protecting food products. To enhance their mechanical properties and functionality, these films are typically produced by combining starch with plasticisers, crosslinking agents, and other additives through processes such as solvent casting, extrusion, or compression moulding. Starch-based films offer several benefits, including biodegradability, good barrier properties, and suitability for various food applications. Recent studies have demonstrated the effects of red pigment extract incorporation on film properties such as transparency and water vapor permeability (WVP). For example, methylcellulose-based films with red pigment extract showed improved UV barrier properties, reduced transparency but increased WVP, which poses challenges for moisture control (Chen et al., 2023). In contrast, films combining red pigment with methylcellulose and zinc alginate matrices exhibited enhanced thermal stability, mechanical strength and reduced WVP, offering better moisture resistance and improved protective functionality (Wang, 2024).

The fabrication of starch films incorporating red spinach extract has not been widely reported. Owing to the natural pigmentation and antioxidant properties of betacyanin, red spinach extract shows strong potential for use in edible films intended for fruit coatings. Such films can enhance the quality and shelf life of perishable products by functioning as protective barriers. However, incorporating betacyanin into starch-based films presents notable technological challenges and leads to observable changes in the films' functional and physical properties. As a result, the development of smart, biodegradable films using betacyanin is currently receiving significant research attention.

The aim of this study is to investigate the effect of different red spinach extract concentrations (4%, 60%, and 80% w/w polymer) on the transparency and water vapour permeability of starch films. This evaluation seeks to determine their potential for fruit preservation, with the scope focusing specifically on the films' optical properties and their barrier performance against water and light.

2. MATERIALS AND METHODS

2.1 Chemicals and Materials

Ethanol, 2,2-dipgenyl-1-picrylhydrazyl (DPPH), Glycerol, Silica gel, and Gallic acid were obtained from Chemiz, Malaysia. Sodium Carbonate and Folin Chiocalteu reagent were obtained from Sigma, United States, Tapioca starch was obtained from local hypermarket.

2.2 Sample preparation of *Amaranthus dubius*

Red spinach (leaves and stem) were obtained from local farmers. The red spinach was thoroughly cleaned under running water to remove any impurities and carefully patted dry with a clean towel to remove surface moisture. Then, it was dried using a food dehydrator (Excalibur, USA) set at 52 ˚C until it reached a constant dry weight. After drying, the red spinach was ground into fine powder using a laboratory blender (Dessini, Italy) to increase the surface area, which aids in the efficiency of the extraction process. The powdered red spinach sample was transferred into a clean container and stored in a chiller (Arneg, Philippines) at 4 ˚C until further analysis to preserve its stability.

2.3 Extraction of *Amaranthus dubius*

Red spinach was extracted using 50% ethanol by adding 5g of dried red spinach powder in 50 ml ethanol. The mixture was stirred occasionally for 15 minutes at 25 ˚C. Then, the mixture was subjected to ultrasound extraction at 40 kHz frequency, at 25 ˚C for 15 minutes using ultrasonic bath (Daihan, Korea). After sonication, the mixture was filtered and vaporized to separate the liquid extract from solid residues. The filtrate was collected for subsequent analysis. All extractions were performed in triplicate to ensure accuracy and reproducibility.

2.4 Preparation of film containing *Amaranthus dubius*

The film sheet preparation method involved incorporating red spinach extract with tapioca starch and glycerol as the film-forming matrix. First, 46.25 mL of distilled water was heated on a hot plate to 80-90 ˚C. Then, 2.5g of tapioca starch was added to the heated water and stirred continuously until completely dissolved. Subsequently, 0.25g of glycerol was incorporated as a plasticizer, and the mixture was allowed to cool to room temperature. Once cooled, 1 mL of red spinach extract, at concentrations of 40%, 60%, and 80% w/w polymer, was added thoroughly to ensure uniform distribution of the extract throughout the film-forming solution. The homogenous film mixture was then evenly poured onto a film plate and spread uniformly. The film plate was placed in an oven (Memmert, Netherlands) at 45 ˚C for 2 hours to facilitate initial drying, followed by air-drying at room temperature for several days to complete the drying process and obtain stable film sheets.

2.5 Film analysis

2.5.1 Light barrier of film

The light barrier of the film was evaluated using a UV-vis spectrophotometer (Shimadzu, Japan) following a report by Mora-Palma et al., (2024). The small rectangular samples of the dried film were prepared and placed perpendicular to the light path in a cuvette. The absorbance of each film sample was measured at different wavelength, including 200, 280, 350, 400, 500, 600, 700, and 800 nm, with an empty cell used as a blank. Measurements were performed in triplicate to ensure accuracy. The percentage transmission (T) of the films was calculated using equation (1) where A is the absorbance of the film at 200 – 800 nm.

$$\%T = 10^{-A} \times 100 \quad (1)$$

2.5.2 Water Vapour Permeability (WVP)

The water vapour (WVP) of the films were determined based on the method described by Pop et al., (2024). A piece of the film was carefully attached to the opening of a small aluminium cup (4.6

cm diameter) containing approximately 5g of anhydrous silica gel to maintain a dry environment inside the cup. The assembly was initially weighed using weighing balance (Mettler Toledo, Switzerland) and then placed inside a desiccator containing water vapor to create a high-humidity environment outside the cup. The assembly was weighed daily to measure the mass increase caused by water vapor permeating through the film and being absorbed by the silica gel. The water vapor permeation rate was calculated as the mass gain per unit time. The WVP was then calculated using equation (2), where the w is the mass increase due to water vapor absorption by silica gel (grams), x is the thickness of the film (meters), A is the contact surface area of the film (square meter), t is the time interval (days), Δp is the difference in partial water vapor pressure across the film (Pascals).

$$WVP\ \left(\frac{g}{d}.m.Pa\right) = \frac{w.x}{A.t.\Delta p} \quad (2)$$

3. RESULTS AND DISCUSSION

3.1 Light barrier of film

Figure 1 shows that the light transmission of the films increased as the concentrations of red spinach extract increased from 40% to 80% w/w polymer.

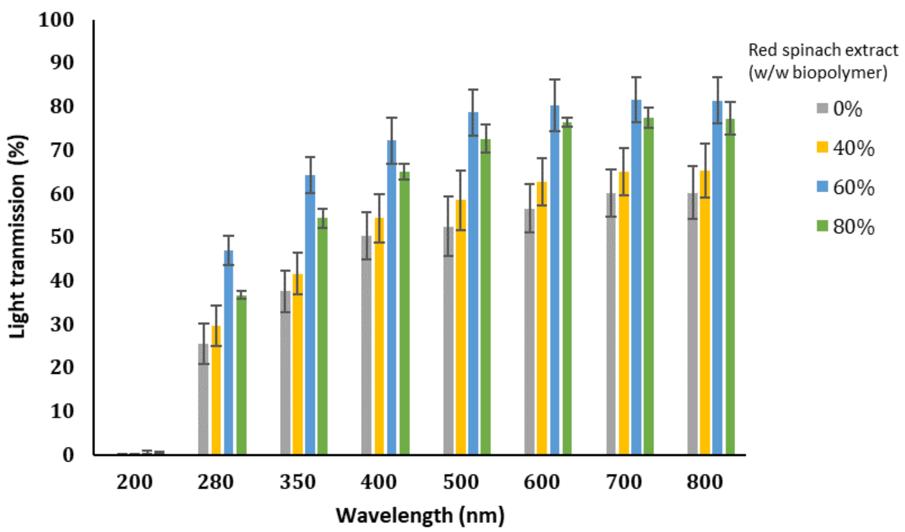

Figure 1: Transmission (%) of film with different concentration of red spinach extract at different wavelengths (nm).

In general, transmission increased across the wavelength ranging from 200 nm to 800 nm. Light scattering is inversely proportional to wavelength. At shorter wavelengths like UV light, scattering is higher, thus lowering transmission. At longer wavelengths (red/NIR), scattering decreases, allowing more light to pass through (Kakiuchida & Ogiwara, 2024). At each wavelength, it can be seen that transmission increased up to 60% extract and decreased when 80% extract was used. Adding red spinach extract introduces polyphenols and betacyanins that can interact with the starch biopolymer matrix. Up to 60%, these interactions reduce polymer aggregation and scattering, making the film more compact and allowing more light to pass through (Hasan et al., 2025).

At very high extract concentration (80%), betacyanin strongly absorbs in the visible region (especially 480-540 nm) reducing transmission, thus the extract natural colour dominates. These pigments contain conjugated double bonds that interact strongly with shorter wavelengths of light (such as UV rays), leading to increased absorption and scattering of light rather than transmission through the film (Jaakola et al., 2017). Excess extract may also exceed the compatibility limit with the biopolymer leading to pigment/polyphenol aggregation. This situation creates light scattering centres thus lowering the transmission. This result shows a different trend with a previous study conducted by Nainggolan et al., (2015). In their report, the transmission of the film decreased with red pigment content up to 15%, but increased at 20% due to agglomeration of minerals which increases particle-particle reactions in fruit coating application. In general, the amount of pigment molecules in fruit coatings grows as the concentration of red spinach extract rises. This makes the coating better at absorbing and scattering UV light, providing good UV protection. Transmission (high opacity) in the UV region (200–400 nm) less than 10% (<10%) is an ideal value for UV-protective film (Tie et al., 2026). This UV-blocking trait is very important because it keeps nutrients, pigments, and structural parts of the fruit from breaking down faster due to UV radiation (Darré et al., 2022). According to Bowden, (2023), the coating also works as a physical barrier, keeping moisture in and controlling gas exchange, especially oxygen and ethylene, which are important in the ripening and senescence processes.

3.2 Water vapour permeability (WVP) of film

The WVP of films with different concentrations of red spinach extract (40%, 60%, and 80% w/w polymer) were studied over 7 days as shown in in Table 1.

Table 1: Water vapor permeability of film using three different concentration of red spinach extract for 7 days

Day	Water Vapor Permeability, WVP (g/d. m. Pa)			
	Concentration of Red Spinach Extract (% w/w polymer)			
	Control (0%)	**40%**	**60%**	**80%**
0	0	0	0	0
1	$1.33 \pm 0.10 \times 10^{-6}$ D_a	$1.43 \pm 0.10 \times 10^{-6}$ C_a	$1.88 \pm 0.01 \times 10^{-6}$ A_a	$1.72 \pm 0.09 \times 10^{-6}$ B_a
2	$1.22 \pm 0.09 \times 10^{-6}$ D_a	$1.32 \pm 0.09 \times 10^{-6}$ C_a	$1.54 \pm 0.05 \times 10^{-6}$ B_b	$1.60 \pm 0.02 \times 10^{-6}$ A_a
3	$1.17 \pm 0.08 \times 10^{-6}$ D_b	$1.19 \pm 0.08 \times 10^{-6}$ C_b	$1.29 \pm 0.02 \times 10^{-6}$ B_c	$1.40 \pm 0.09 \times 10^{-6}$ A_b
4	$0.98 \pm 0.03 \times 10^{-6}$ D_c	$1.00 \pm 0.03 \times 10^{-6}$ C_c	$1.07 \pm 0.04 \times 10^{-6}$ B_d	$1.11 \pm 0.04 \times 10^{-6}$ A_c
5	$7.92 \pm 0.31 \times 10^{-7}$ D_c	$8.92 \pm 0.31 \times 10^{-7}$ C_c	$9.15 \pm 0.17 \times 10^{-7}$ B_e	$9.61 \pm 0.22 \times 10^{-7}$ A_d
6	$6.45 \pm 0.25 \times 10^{-7}$ D_d	$7.45 \pm 0.25 \times 10^{-7}$ C_d	$7.63 \pm 0.13 \times 10^{-7}$ B_f	$8.06 \pm 0.18 \times 10^{-7}$ A_e
7	$5.39 \pm 0.22 \times 10^{-7}$ D_d	$6.39 \pm 0.22 \times 10^{-7}$ C_d	$6.77 \pm 0.20 \times 10^{-7}$ B_g	$7.04 \pm 0.11 \times 10^{-7}$ A_e

Water vapor permeabilities are mean $\pm$ SD (n = 3) based on film with different concentration of red spinach extract w/w polymer. Different capital letter superscripts within the same row and different small letter superscripts within the same column indicates significant

Initially, at day 1, the WVP was highest in the film with 60% extract (1.88 x 10^{-6} g/d.m.Pa), followed by 80% (1.72 x 10^{-6} g/d.m.Pa) and 40% (1.43 x 10^{-6}). The higher initial WVP is attributed to hydrophilic compounds such as polyphenols and betacyanin in the extract, which can form micro-pathways allowing water vapor diffusion (Le et al., 2024). Over time, WVP decreased for all films as the film structure became more compact and stable due to drying and moisture evaporation, which reduced the vapor transmission pathways. On day 7, the film with 40% extract showed the lowest WVP (6.39 x 10^{-7} g/d.m.Pa), while 60% and 80% films had slightly higher values, likely due to the higher hydrophilic content slowing film stabilization. The incorporation of red spinach extract reduced the water vapour permeability below typical values for food packaging films (1.81 x 10^{-2} g/d.m.Pa) (Sahu & Khokhar, 2024), indicating enhanced barrier properties. Lower WVP helps minimize moisture loss, preserving the texture, firmness, and overall freshness of coated fruits, thus extending shelf life (Falguera et al., 2011). The pigment molecules in the extract interact with the film matrix, improving barrier properties and regulating moisture exchange effectively (Radev, 2017).

4. CONCLUSION

The content of red spinach extract plays an important role in changing the transparency and water vapor permeability of the film, thus it presents as a potential multi-functional solution to fruit coatings. Higher concentrations of the extract improved UV protection through increased pigment content due to increased absorption and dispersion of UV light. Nevertheless, the transmission of the film decreased with addition of 80% red spinach extract due to stronger absorption of light at this concentration. The extract also enhanced film barrier properties. Water vapour permeability decreased along with time and it contributed to less moisture loss and dehydration, showing high potential for fruit coating applications.

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