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Characterization of a Smart Bioplastic Based on Porang Glucomannan, Sodium Alginate, and Purple Corn Extract (*Zea mays* L.) as a Potential Freshness Indicator

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ABSTRACT

Smart bioplastic is created using natural polymers and anthocyanins that respond to pH changes. This study aimed to characterize the incorporation of purple corn extract (0%, 10%, 30%, and 50%) as an anthocyanin source into a porang glucomannan–alginate-based smart bioplastic. The smart bioplastics were characterized for physico-mechanical and barrier properties, and preliminary application as freshness indicators using pH and ammonia-sensitivity tests. The smart bioplastic showed color changes (ΔE*) of 1.68–52.98, opacity of 1.52–3.13 A600/mm, thickness of 0.146–0.171 mm, tensile strength from 5.28–7.42 MPa, and elongation at break from 38.70–65.39%. Moreover, smart bioplastics presented water content from 18.98–29.59%, water solubility from 50.53–60.18%, swelling index from 7.17–12.04%, water vapour permeability from 0.239–0.288 g·mm/m^2·kPa·h, and water contact angle from 31.41–43.31°. Application tests showed colour changes (ΔE*) induced by pH changes (9.03–63.99) and ammonia vapour (7.39–34.98). The incorporation of purple corn extract yielded a smart bioplastic with suitable functional properties and strong responses to pH changes and ammonia vapour, indicating its potential as a visual freshness indicator for food packaging applications. In addition, future studies should examine the food freshness-monitoring ability, for example, the freshness of refrigerated shrimp during storage.

1. INTRODUCTION

The growing threat of plastic waste to the environment has driven innovation in environmentally friendly packaging, such as edible bioplastics to replace synthetic polymers in food packaging [1]. Various types of packaging materials, including active and biodegradable options, continue to be developed to meet increasing market demand and evolving consumer needs. However, as food safety awareness grows, consumer information needs to be comprehensive and easily accessible, including expiration dates. Recently, bioplastic has been developed into a smart bioplastic, which is bio-based and contains natural anthocyanins [2]. Smart bioplastics can monitor changes in food freshness in real-time by detecting variations in the food packaging environment, such as temperature fluctuations, gas changes, and other factors [3], providing fast, accurate, and easily visible information on food freshness [4].

Perishable food, such as fish and shrimp are susceptible to quality deterioration since it has high nutritional content. The deterioration process can be caused by autolytic (enzymatic and chemical) processes, oxidation, bacteriological processes, and dehydration [5]. This can result in both economic losses and danger to consumer health. Quality deterioration in shrimp is usually characterized by physical changes, such as soft texture, colour changes, and pungent odour [6]. However, consumers often struggle to assess a product's freshness directly. Therefore, the development of innovative packaging technology in this area is urgently needed, especially for perishable products such as fish and shrimp.

One approach to overcoming this problem is the use of smart packaging, such as a smart bioplastic, which can detect changes in pH through colour changes [7]. The quality of perishable products, such as vannamei shrimp, is often associated with increased pH due to the formation of volatile compounds from decomposed protein [8]. Therefore, pH-responsive smart bioplastics have attracted considerable attention as potential visual indicators of spoilage-related chemical changes. However, the development of such materials requires environmentally friendly and effective biopolymer matrices to support sustainability in modern food packaging applications.

One potential base material for making a smart bioplastic is a combination of glucomannan and alginate. Glucomannan is a natural polysaccharide with good mechanical properties and is popular for making safe and environmentally friendly packaging [9], including flexibility, transparency, the ability to form a strong matrix, and high biodegradability. In addition, alginate is a natural polysaccharide obtained from seaweed, which has good film-forming ability and hydrocolloid properties that enable the formation of an elastic and strong bioplastic structure [10]. The combination of porang glucomannan and alginate can produce a bioplastic with optimal mechanical characteristics, such as high elasticity and rapid biodegradability, making it suitable for use as a base material for a smart bioplastic.

The development of a smart bioplastic that changes colour according to pH changes requires natural colour indicators that are sensitive to pH changes, such as anthocyanins [4]. Anthocyanins are natural pigments that belong to the flavonoid group and have halochromic properties, which are colour changes influenced by pH changes [11]. One source of natural anthocyanins is purple corn (*Zea mays* L.). These characteristics make purple corn extract a suitable choice for application in the development of a smart bioplastic for monitoring food freshness.

Several intelligent packaging bioplastics based on natural anthocyanins have been developed using starch, chitosan, cellulose derivatives, and alginate matrices for monitoring food freshness through colour changes [12, 13]. Previous studies have successfully incorporated anthocyanins from red cabbage, purple sweet potato, and other plant sources into pH-responsive indicator films [14, 15]. However, information regarding the use of porang glucomannan as the primary bioplastic-forming matrix remains limited, particularly when combined with sodium alginate and purple corn extract. Moreover, the physicochemical characteristics and indicator performance of porang glucomannan–alginate smart bioplastic containing purple corn anthocyanins have not been well documented. Therefore, further investigation is required to evaluate the suitability of this biopolymer combination as a smart bioplastic for freshness-indicator applications.

The use of natural biopolymer-based bioplastics is hypothesized to have various advantages. In addition to being environmentally friendly, they function as a freshness detection system that provides added value for consumers and producers [16]. The development of this smart bioplastic technology is also in line with global efforts to reduce and replace the use of conventional plastics that are difficult to decompose with a more sustainable material [17]. This study aims to develop and characterize a porang glucomannan–alginate-based smart bioplastic incorporating anthocyanins from purple corn extract and to evaluate its pH and ammonia responsiveness as a potential visual indicator of spoilage-related chemical changes.

2. MATERIAL AND METHODS

2.1 Material

The raw materials used were commercial porang glucomannan powder containing 70% glucomannan (Exa Shop, Bantul, Indonesia), sodium alginate (Exa Shop, Bantul, Indonesia), purple corn (*Zea mays* L.) obtained from Hokky Supermarket (Indonesia), glycerol, distilled water, citric acid, hydrochloric acid (HCl), and sodium hydroxide (NaOH). All chemicals used were of analytical grade.

2.2 Method

2.2.1 Research design

The research design used was completely randomized. The treatment in this study referred to Abdillah et al. [1] with modifications. Each treatment in this study was repeated three times. The treatments tested were differences in the concentration of purple corn extract additions: PC0 (0%), PC1 (10%), PC2 (30%), and PC3 (50%). The extract concentrations were calculated on a volume basis (v/v) relative to the initial volume of the bioplastic-forming solution (20 mL). The formulation of each treatment is presented in Table 1.

Table 1. Formulation of smart bioplastic containing different concentrations of purple corn extract

Treatment	Porang Glucomannan (g)	Sodium Alginate (g)	Glycerol (mL)	Purple Corn Extract (mL)
PC0	0.4	0.4	0.24	0
PC1	0.4	0.4	0.24	2
PC2	0.4	0.4	0.24	6
PC3	0.4	0.4	0.24	10

2.2.2 Purple corn extract production

The extraction process of purple corn was carried out by boiling it in distilled water. This method was modified from the research conducted by Abdillah et al. [18]. Purple corn was boiled using a 1:1 ratio at a temperature of 90 ℃ for 60 min. After that, the boiled mixture is filtered to separate the pulp from the solution, and the solution is then centrifuged at a speed of 4000 rpm for 30 min to separate the extract from the insoluble material.

2.2.3 Total anthocyanin content

The determination of total anthocyanin content in purple corn extract was carried out using the pH-differential method, referring to the research by Wahyuningsih et al. [19]. This method utilises the difference in the absorbance of anthocyanin extract at two pH conditions, namely pH 1.0 and pH 4.5. Absorbance measurements were performed at the maximum visible wavelength (λ vis-max) of 520 nm, as well as at 700 nm to correct the effect of solution turbidity. The total anthocyanin content was calculated in cyanidin-3-glucoside using the following Eq. (1):

$$\text{Total anthocyanin (mg/L)} = \frac{(A \times \text{MW} \times \text{DF} \times 1000)}{(\varepsilon \times l)} \quad (1)$$

where, *A* is a difference in sample absorbance; *MW* is molecular mass of cyanidin-3-glucoside (449.2 g/mol); *DF* is dilution factor of the extract; *ε* is molar absorptivity coefficient of cyanidin-3-glucoside (26.965 L/mol·cm); *l* is path length of the cuvette.

2.2.4 Smart bioplastic production

The bioplastic production in this study refers to Abdillah et al. [1] with modifications. The film-forming solution consisted of 0.4 g porang glucomannan, 0.4 g sodium alginate, 0.24 mL glycerol, and 18.96 mL distilled water. Porang glucomannan was dissolved in distilled water and heated at 80 °C for 5 min while stirring continuously at 200 rpm. Sodium alginate was then gradually added and stirred for 2 min. Subsequently, glycerol (30%, v/w based on total polymer weight) was added as a plasticizer, and the mixture was stirred for an additional 3 min. Purple corn extract was incorporated at concentrations of 10%, 30%, and 50% (v/v), corresponding to 2, 6, and 10 mL of extract, respectively. The resulting solution was stirred for 3 min, poured into disposable Petri dishes, and dried at 38 °C for 12 h. The dried films were removed and stored in sealed plastic clips containing silica gel until further analysis.

2.2.5 Visual appearance

The visual appearance of films with purple corn extract added was determined by observing three main characteristics: transparency, surface smoothness, and colour homogeneity [1]. Transparency was assessed by comparing the film's ability to transmit light before and after the addition of the extract, resulting in a clearer and more transparent visual appearance. Surface smoothness was measured by observing changes in texture, where the use of extract was expected to produce a flatter and smoother surface, providing a better aesthetic impression. In addition, colour homogeneity was analysed by observing the diversity of colouring on the film, which indicated an even distribution of purple corn extract, creating a consistent and attractive appearance.

2.2.6 Colour properties

Based on the CIELAB colour space, the method described in research [20] was followed to determine the colour parameters of the smart bioplastic, including brightness or lightness (L^*), redness or greenness (a^*), yellowness or blueness (b^*), and total colour difference (ΔE^*), calculated using Eq. (2):

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (2)$$

2.2.7 Opacity

The opacity of purple corn extract smart bioplastic was measured using a spectrophotometer to measure absorbance and transmittance using air as a reference, scanning in the wavelength range of 200-800 nm [21]. Film turbidity can be measured using the following Eq. (3):

$$Opacity = \frac{\text{Absorbance 600 nm}}{\text{Thickness film}} \quad (3)$$

2.2.8 Thickness

Film thickness was measured using a Syntek digital micrometer, which has an accuracy of ±0.001 mm [1]. Ten different parts of the film sample were taken as test points to ensure an even thickness distribution across the entire film surface. This measurement is important in determining a film's overall quality, as variations in thickness can affect physical characteristics and visual appearance, including durability and elasticity. With a highly precise tool, even small changes in thickness can be identified, providing a complete picture of the homogeneity and uniformity of the film structure.

2.2.9 Tensile strength and elongation at break

Tensile strength and elongation at break tests were conducted using a testometric tensile testing machine in accordance with BS EN ISO 527–3 (1996) standards, following the method [22]. Film samples were cut into squares measuring 25 mm wide and 50 mm long. The pieces were then mounted on the testing device with a distance of 50 mm between the handles. The tensile test was conducted at a speed of 5 mm/min at room temperature. The results obtained were tensile strength and elongation percentage values, which were presented in numerical and graphical form.

2.2.10 Moisture content and water solubility

Moisture content and water solubility are two important parameters in film characteristic analysis. The moisture content and water solubility methods follow the method of study [23]. Moisture content describes the amount of water remaining in the film after the drying process, while water solubility indicates how much the film can dissolve when in contact with water. To determine the moisture content, a 20 mm × 20 mm film sample was dried in an oven at 105 °C for 24 h. After that, water solubility was measured by immersing the dry sample in 30 mL of deionised water and incubating it in a water bath at a temperature of 25 °C, and shaking it at 50 rpm for 24 h. After the incubation, the remaining insoluble film was filtered using filter paper and dried again in an oven at a temperature of 105 °C for 24 h. Calculation of water content and water solubility using Eqs. (4) and (5).

$$WaterContent(\%) = \left(\frac{\text{weight sample} - \text{weight of dry sample}}{\text{weight sample}}\right) \times 100 \quad (4)$$

$$WS(\%) = \left[\left(\frac{W_0 - W_1}{W_0}\right) \times 100\right] \quad (5)$$

2.2.11 Water vapour permeability

Water vapour permeability is a crucial parameter used to assess a film's ability to block or allow water vapour to pass through its surface. The method used follows that of the study [24]. In this study, the film was applied as a cover to a glass bottle containing 10 g of dry silica gel, which was stored in a desiccator at 90% relative humidity and 25 °C. Every 24 h for a period of 7 days, the bottles were weighed to monitor changes in weight due to water vapour absorption by the silica gel. These weight measurements provided data on the amount of water vapour that successfully passed through the film. To analyse the data, the linear slope of the measured weight over time was recorded, which can be calculated using the linear Eqs. (6) and (7):

$$WTVR = \left(\frac{g}{m^2.\ h}\right) = \left[\frac{\text{slope}}{\text{area}}\right] \quad (6)$$

$$WVP = \left(\frac{g.\ \text{mm}}{m^2.\ h.\text{kPa}}\right) = \left[\left(\frac{\text{WTVR} \times \text{film thickness}}{S \times (\text{RH}_2 - \text{RH}_1)}\right)\right] \quad (7)$$

where, WTVR is a water vapour transmission rate (g/m^2 h); *S* is saturation pressure of water (kPa) in the test chamber; RH_1 is relative humidity of dry silica; RH_2 is relative humidity of the test chamber.

2.2.12 Swelling index

The swelling index is measured to determine the film's ability to absorb water. The swelling index of a film is determined by immersing a film strip (20 mm × 20 mm) in deionized water at a temperature of 25 °C for 60 min [23]. The swelling index can be expressed using the following Eq. (8):

$$Swelling\ Index(\%) = \left[\left(\frac{W_1 - W_0}{W_0}\right) \times 100\right] \tag{8}$$

where, W_0 is the initial weight of the film (g); W_1 is the weight of the film after soaking in deionized water (g).

2.2.13 Water contact angle

The water contact angle on the purple corn extract indicator film was measured using a drop of deionised water (10 µL) carefully placed on the film surface, then the water contact angle was photographed using a digital microscope with 1000× magnification after 10 seconds. The WCA value (n = 3) was obtained using image software [19].

2.2.14 pH sensitivity

The smart bioplastic was cut into small 1 cm × 1 cm squares, then dipped into buffer solutions with pH variations between 1 and 13. Colour changes in the film were observed within 2 to 7 min after immersion. This colour change was measured using a colorimeter, referring to the study by Abdillah et al. [1]. The colour parameters of the smart bioplastic, including the brightness or lightness (L^*), red or green (a^*), yellow or blue (b^*), and total colour difference (ΔE^*), were calculated using the same equation as in the colour change measurement.

2.2.15 Ammonia sensitivity

The sensitivity of the smart bioplastic to ammonia was determined based on the method used by Abdillah et al. [1]. Film samples were placed at a distance of 10 mm above a 0.8 M ammonia solution (80 mL), which produced ammonia vapour to test the colour response of the film. Colour changes (R, G, and B values) of the smart bioplastic were observed periodically using a colorimeter every 4 min, until the total testing time reached 24 min. These colour changes were calculated as the percentage of sensitivity to ammonia (SRGB) using the following Eq. (9):

$$SRGB\% = \frac{(\text{R1-R2}) + (\text{G1-G2}) + (\text{B1-B2})}{\text{R1+G1+B1}} \times 100 \tag{9}$$

where, R_1, G_1, and B_1 are the initial colour values of the smart bioplastic before exposure to ammonia; R_2, G_2, and B_2 are the colour values after exposure.

2.2.16 Data analysis

The quantitative data were presented at least in triplicate and were analysed using the Analysis of Variance (ANOVA) followed by Duncan's Multiple Range Test at a significance level of $p \leq 0.05$ using IBM SPSS version 12.

3. RESULTS AND DISCUSSION

3.1 Results

3.1.1 Total anthocyanin content

Based on calculations using the pH-differential method, the total anthocyanin content in purple corn extract was 257.15 mg/L. This result represents the amount of anthocyanin compounds contained in the extract using the cyanidin-3-glucoside molecular standard. This shows that purple corn extract has a fairly high anthocyanin content.

3.1.2 Visual appearance

The visual appearance of smart bioplastics made from alginate and porang flour with the addition of purple corn extract at different concentrations is shown in Figure 1. The control treatment showed a colourless and transparent film with high image visibility (letters and logo). The addition of purple corn extract to the smart bioplastic produced a different visual appearance, as it turned red. The transparency level produced by the smart bioplastic was influenced by the increase in the concentration of purple corn extract added. The higher the concentration, the lower the image visibility of the coated indicator (letters and logos).

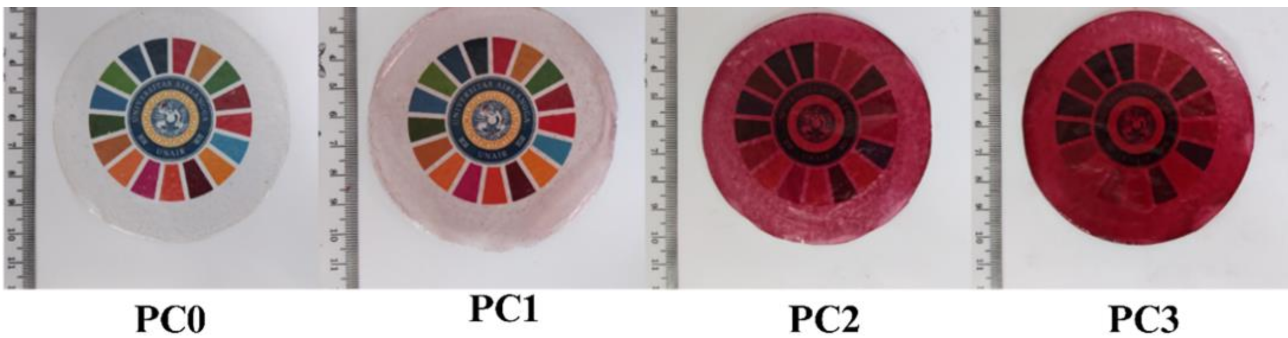

Figure 1. The visual appearance of smart sustainable bioplastic

Note: PC0 is porang glucomannan- sodium alginate with no purple corn extract; PC1 is porang glucomannan- sodium alginate with 10% purple corn extract; PC2 is porang glucomannan- sodium alginate with 30% purple corn extract; and PC3 is porang glucomannan- sodium alginate with 50% purple corn extract.

The addition of purple corn extract to the smart bioplastic affects the level of surface smoothness, resulting in small bubbles, as seen in the PC1 treatment. An increase in the concentration of purple corn extract produced more bubbles on the surface of the smart bioplastic, as can be seen in the PC2 and PC3 treatments. The level of colour homogeneity in the smart bioplastic in treatments PC1, PC2, and PC3 appears to be even, but in treatment PC1, the colour produced in the smart bioplastic appears to be unpigmented, similar to the control treatment PC0.

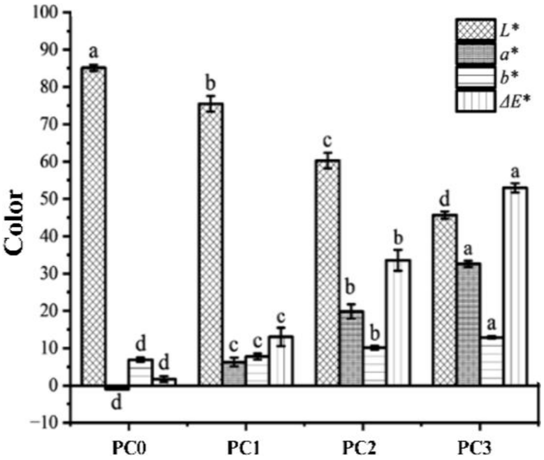

Figure 2. The color properties of smart bioplastic
Note: PC0 is porang glucomannan- sodium alginate with no purple corn extract; PC1 is porang glucomannan- sodium alginate with 10% purple corn extract; PC2 is porang glucomannan- sodium alginate with 30% purple corn extract; and PC3 is porang glucomannan- sodium alginate with 50% purple corn extract. Differences superscript letters indicate significant results at $p < 0.05$.

3.1.3 Appearance of smart bioplastic colour

Colour analysis of the smart bioplastics included lightness (L^*), redness (a^*), yellowness/blueness (b^*), and total colour difference (ΔE^*). ANOVA showed that the addition of purple corn extract significantly affected all colour parameters ($p < 0.05$). The highest L^* value was observed in the control film (PC0; 85.13), while the lowest was found in the film containing 50% extract (PC3; 45.67), which differed significantly from PC1 (75.49) and PC2 (60.26). Increasing extract concentration resulted in a progressive decrease in lightness.

Conversely, redness (a^*) increased significantly with extract concentration, with the highest value recorded in PC3 (32.61) and the lowest in the control (–0.97), followed by PC1 (6.26) and PC2 (19.81). A similar trend was observed for b^*, where PC3 showed the highest value (12.87), compared to PC0 (6.89), PC1 (7.74), and PC2 (10.10). The total colour difference (ΔE^*) also increased significantly ($p < 0.05$), ranging from 1.68 in the control to 52.96 in PC3, with intermediate values in PC1 (13.01) and PC2 (33.54). Overall, higher concentrations of purple corn extract reduced lightness but enhanced redness, b^* values, and total colour difference, with PC3 exhibiting the most pronounced colour change (Figure 2).

3.1.4 Opacity

The results of opacity testing of the addition of purple corn extract in the ANOVA showed a significant effect ($p < 0.05$). The highest opacity was shown by the smart bioplastic with the addition of 50% purple corn extract (PC3) of 3.13, while the lowest opacity was shown by the control smart bioplastic (PC0) of 1.52 which was significantly different from the 10% smart bioplastic (PC1) of 2.21 and the 30% smart bioplastic (PC2) of 2.61. The results show that the higher the concentration of purple corn extract, the higher the opacity value of the smart bioplastic. The opacity of alginate and porang flour smart bioplastics with the addition of corn extract is shown in Table 2.

Table 2. The physico-mechanical properties and barrier properties of smart sustainable bioplastic

Parameters	PC0	PC1	PC2	PC3
Thickness (mm)	0.146 ± 0.003^{d}	0.153 ± 0.002^{c}	0.161 ± 0.003^{b}	0.171 ± 0.001^{a}
Elongation at Break (%)	38.70 ± 6.29^{b}	54.03 ± 7.76^{a}	65.39 ± 4.70^{a}	59.31 ± 6.70^{a}
Tensile Strength (MPa)	5.28 ± 0.99^{b}	5.29 ± 1.40^{b}	6.71 ± 0.76^{ab}	7.43 ± 0.40^{a}
Swelling index (%)	12.04 ± 3.46^{a}	10.99 ± 1.67^{a}	9.57 ± 2.83^{ab}	7.17 ± 1.46^{b}
WVP (g·mm/m²·kPa·h)	0.2390 ± 0.0165^{cb}	0.2636 ± 0.0148^{ab}	0.2866 ± 0.0245^{a}	0.2878 ± 0.0225^{a}
Opacity	1.52 ± 0.34^{d}	2.21 ± 0.16^{c}	2.61 ± 0.31^{b}	3.13 ± 0.15^{a}
WCA (°)	43.31 ± 4.85^{a}	36.11 ± 4.57^{b}	34.74 ± 3.57^{b}	31.41 ± 3.59^{b}
Water Solubility (%)	50.53 ± 6.15^{a}	60.18 ± 9.80^{a}	55.60 ± 13.93^{a}	57.59 ± 10.74^{a}
Moisture content (%)	18.98 ± 6.35^{b}	26.27 ± 3.11^{a}	25.52 ± 2.55^{a}	29.59 ± 3.98^{a}

Note: PC0 is porang glucomannan- sodium alginate with no purple corn extract; PC1 is porang glucomannan- sodium alginate with 10% purple corn extract; PC2 is porang glucomannan- sodium alginate with 30% purple corn extract; and PC3 is porang glucomannan- sodium alginate with 50% purple corn extract. WCA: Water contact angle. Differences superscript letters indicate significant results at $p < 0.05$.

3.1.5 Thickness

The results of thickness testing of the addition of purple corn extract in the ANOVA showed a significant effect ($p < 0.05$). The highest thickness was shown by the smart bioplastic with the addition of 50% purple corn extract (PC3) of 0.171 mm, while the lowest thickness was shown by the control smart bioplastic (PC0) of 0.146 mm and was significantly different from the 10% smart bioplastic (PC1) of 0.153 mm and the 30% smart bioplastic (PC2) of 0.161 mm. The results indicate that the higher the concentration of purple corn extract added, the higher the thickness value of the smart bioplastic. The thickness of the alginate and porang flour smart bioplastics with the addition of corn extract is shown in Table 2.

3.1.6 Tensile strength and elongation at break of smart bioplastic

The tensile strength test results of the addition of purple corn extract in the ANOVA showed a significant effect ($p < 0.05$). The highest tensile strength was shown by smart bioplastic with the addition of 50% purple corn extract (PC3) at 7.43 MPa, but this was not significantly different from smart bioplastic with 30% (PC2) at 6.71 MPa. The lowest tensile strength was shown by the control smart bioplastic (PC0) at 5.28 MPa and the control smart bioplastic with 10% (PC1) at 5.29 MPa. The results indicate that the higher the concentration of purple corn extract added, the higher the tensile strength value of the smart bioplastic. The tensile strength of alginate and porang flour smart bioplastics with the addition of corn extract is shown in Table 2.

The results of the elongation at break test of the addition of purple corn extract in the ANOVA showed a significant effect ($p < 0.05$). The highest elongation at break was shown by the smart bioplastic with the addition of 10% purple corn extract (PC1) at 54.03, 30% smart bioplastic (PC2) was 65.39, smart bioplastic 50% (PC3) was 59.31%, and the lowest elongation at break was shown by the control smart bioplastic (PC0) at 38.70%. The addition of purple corn extract was proven to increase elongation at break compared to the control (without extract). The elongation at break of alginate and porang flour smart bioplastics with the addition of corn extract is shown in Table 2.

The increase in the elongation value of smart bioplastics with the addition of purple corn extract indicates that the extract can improve the elasticity and flexibility of the bioplastic. Bioplastics with the addition of 30% purple corn extract (PC2) produced the highest elongation value, while the control bioplastic (PC0) had the lowest elongation value. The addition of purple corn extract at concentrations of 10%, 30%, and 50% significantly increased the bioplastics' ability to stretch before breaking compared to bioplastics without extract addition. These results indicate that the bioactive content in purple corn extract improves the bioplastic matrix structure, thereby increasing its resistance to tensile force before breaking.

3.1.7 Moisture content and water solubility

The results of moisture content testing with the addition of purple corn extract in the ANOVA showed a significant effect ($p < 0.05$) on the moisture content value of the smart bioplastic. The highest moisture content was shown by the smart bioplastic with the addition of 50% purple corn extract (PC3) at 29.59%, followed by smart bioplastic 10% (PC1) at 26.27%, smart bioplastic 30% (PC2) at 25.52%, and the lowest moisture content was shown by the control smart bioplastic (PC0) at 18.98%. The addition of purple corn extract was proven to increase the water content of smart bioplastics compared to the control (without extract). The higher the concentration of extract added, the higher the water content produced. The water content of alginate and porang flour smart bioplastics with the addition of corn extract is described in Table 2.

The results of water solubility testing of the addition of purple corn extract in the ANOVA showed no significant effect ($p > 0.05$). The water solubility values obtained were as follows: smart bioplastic with the addition of purple corn extract control (PC0) was 50.53%, smart bioplastic 10% (PC1) was 60.18%, smart bioplastic 30% (PC2) was 55.60%, and smart bioplastic 50% (PC3) was 57.59%. The addition of purple corn extract was proven to increase the water solubility compared to the control (without extract). The water solubility of alginate and porang flour smart bioplastics with the addition of corn extract are described in Table 2.

3.1.8 Water vapour permeability

The results of water vapour permeability testing of the addition of purple corn extract in the ANOVA showed a significant effect ($p < 0.05$). The highest water vapour permeability was shown by the smart bioplastic with the addition of 50% purple corn extract (PC3) at 0.288 g·mm/m^2·kPa·h, the smart bioplastic with 30% addition (PC2) showed 0.287 g·mm/m^2·kPa·h, and the lowest water vapour permeability was shown by the control smart bioplastic (PC0) at 0.239 g·mm/m^2·kPa·h, but it was not significantly different from the smart bioplastic with 10% addition (PC1) at 0.264 g·mm/m^2·kPa·h. The results show that the higher the concentration of purple corn extract, the higher the water vapour permeability value in the smart bioplastic. The water vapour permeability of alginate and porang flour smart bioplastics with the addition of corn extract is shown in Table 2.

3.1.9 Swelling index

The results of swelling index testing of the addition of purple corn extract in the ANOVA showed a significant effect ($p < 0.05$). The highest swelling index was shown by smart bioplastic without the addition of purple corn extract (PC0) at 12.04% and smart bioplastic 10% (PC1) at 10.99%, while the lowest swelling index was shown by the 50% smart bioplastic (PC3) at 7.17%, which was not significantly different from the 30% smart bioplastic (PC2) at 9.57%. The results show that the higher the concentration of purple corn extract, the lower the swelling index value in the smart bioplastic. The swelling index of alginate and porang flour smart bioplastics with the addition of corn extract is described in Table 2.

3.1.10 Water contact angle

The results of water contact angle testing of the addition of purple corn extract in the ANOVA showed a significant effect ($p < 0.05$). The highest water contact angle was shown by the smart bioplastic without the addition of purple corn extract (PC0) of 43.31°, and the lowest water contact angle was shown by the 10% smart bioplastic (PC1) of 36.11°, the 50% smart bioplastic (PC3) of 31.40°; however, it was not significantly different from the 30% smart bioplastic (PC2) at 34.74°. The results indicate that the higher the concentration of purple corn extract added, the lower the water contact angle value of the smart bioplastic. The water contact angle of alginate and porang flour smart bioplastics with the addition of corn extract is described in Table 2.

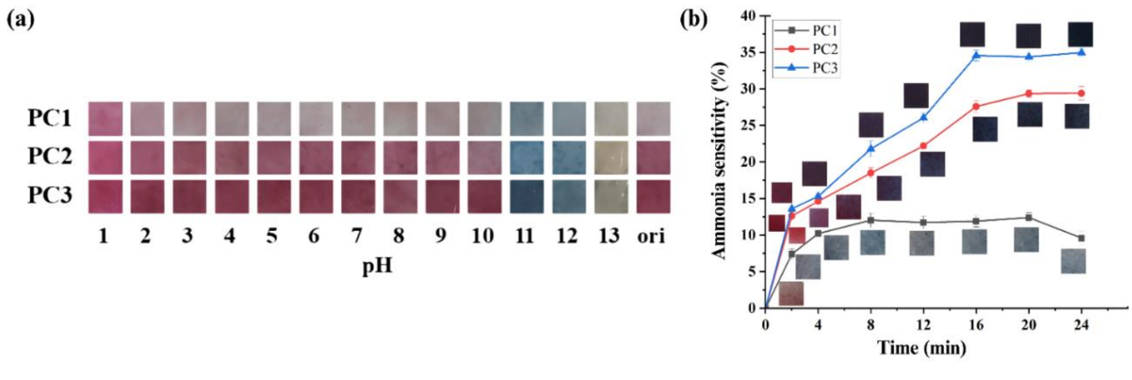

Figure 3. (a) The visual appearance of smart sustainable bioplastic in the different pH, (b) ammonia sensitivity of smart sustainable bioplastic

Note: PC0 is porang glucomannan- sodium alginate with no purple corn extract; PC1 is porang glucomannan- sodium alginate with 10% purple corn extract; PC2 is porang glucomannan- sodium alginate with 30% purple corn extract; and PC3 is porang glucomannan- sodium alginate with 50% purple corn extract.

Table 3. Color change values of the indicator film after immersion in buffer solutions with different pH values

pH	PC1				PC2				PC3			
	L	*a*	*b*	*ΔE**	*L*	*a*	*b*	*ΔE**	*L*	*a*	*b*	*ΔE**
1	64.72 ± 1.09^{f}	35.48 ± 1.82^{a}	-8.81 ± 1.90^{e}	20.63 ± 0.62^{a}	46.34 ± 0.71^{fg}	56.06 ± 2.05^{a}	-2.81 ± 0.85^{c}	19.15 ± 1.91^{de}	36.23 ± 0.88^{f}	59.06 ± 1.51^{a}	5.37 ± 0.47^{b}	14.60 ± 0.26^{d}
2	74.62 ± 1.09^{bcd}	13.03 ± 1.84^{c}	-4.44 ± 0.38^{cd}	10.64 ± 0.50^{de}	43.78 ± 0.40^{g}	39.53 ± 1.24^{b}	-2.13 ± 2.15^{c}	9.43 ± 1.68^{f}	38.08 ± 1.67^{ef}	44.50 ± 1.23^{c}	-3.40 ± 1.20^{cd}	14.80 ± 3.98^{d}
3	76.74 ± 0.73^{b}	9.05 ± 3.06^{d}	-2.35 ± 0.48^{bc}	13.78 ± 0.22^{bc}	53.52 ± 1.98^{c}	30.04 ± 1.10^{cd}	-3.35 ± 0.42^{c}	21.53 ± 3.20^{d}	39.17 ± 1.71^{ef}	40.72 ± 1.63^{d}	-2.79 ± 0.46^{cd}	16.39 ± 4.45^{d}
4	77.09 ± 0.95^{b}	8.40 ± 3.11^{d}	-2.68 ± 0.46^{bc}	14.51 ± 0.35^{b}	52.04 ± 2.49^{cd}	28.82 ± 1.93^{de}	-2.62 ± 0.51^{c}	20.91 ± 3.23^{d}	40.35 ± 1.39^{e}	39.52 ± 2.61^{d}	-2.35 ± 1.84^{cd}	17.72 ± 4.63^{cd}
5	75.73 ± 1.21^{bc}	8.70 ± 1.75^{d}	-2.85 ± 0.41^{bc}	13.25 ± 0.54^{bc}	57.44 ± 1.10^{b}	25.77 ± 3.02^{e}	-3.66 ± 0.23^{c}	27.16 ± 2.32^{c}	45.73 ± 1.32^{bc}	37.14 ± 1.25^{d}	-2.86 ± 1.72^{cd}	23.10 ± 0.71^{bc}
6	72.08 ± 1.69^{de}	10.91 ± 1.84^{cd}	-2.20 ± 0.40^{bc}	9.03 ± 1.22^{e}	50.01 ± 1.30^{de}	29.93 ± 1.82^{cd}	-2.31 ± 1.03^{c}	18.60 ± 3.08^{de}	49.47 ± 1.97^{b}	33.01 ± 5.10^{e}	-2.68 ± 1.57^{cd}	28.13 ± 3.72^{b}
7	75.12 ± 1.48^{bc}	9.07 ± 1.62^{d}	-2.36 ± 0.82^{bc}	12.46 ± 1.62^{bcd}	47.58 ± 0.88^{ef}	32.34 ± 1.15^{c}	-2.01 ± 0.30^{c}	15.24 ± 3.67^{e}	41.94 ± 2.05^{de}	39.38 ± 1.07^{d}	-2.47 ± 0.84^{cd}	18.92 ± 3.12^{cd}
8	75.53 ± 1.33^{bc}	9.79 ± 2.14^{cd}	-2.90 ± 1.05^{bc}	12.46 ± 0.29^{bcd}	52.21 ± 1.08^{cd}	28.82 ± 1.84^{de}	-3.74 ± 0.48^{c}	21.28 ± 4.35^{d}	48.33 ± 3.74^{bc}	33.59 ± 1.37^{e}	-3.74 ± 0.46^{d}	27.23 ± 2.29^{b}
9	72.47 ± 2.28^{de}	9.32 ± 1.04^{d}	-1.23 ± 0.89^{b}	10.40 ± 0.60^{de}	53.42 ± 0.52^{c}	27.02 ± 0.84^{de}	-1.74 ± 0.82^{c}	22.91 ± 3.09^{cd}	40.90 ± 2.11^{e}	39.06 ± 0.31^{d}	-2.43 ± 0.94^{cd}	18.23 ± 4.72^{cd}
10	73.99 ± 0.74^{cde}	8.86 ± 0.50^{d}	-1.97 ± 0.67^{b}	11.78 ± 2.23^{cd}	49.58 ± 2.40^{de}	28.83 ± 1.36^{de}	-2.47 ± 0.51^{c}	19.26 ± 0.72^{de}	41.18 ± 1.19^{e}	38.50 ± 0.86^{d}	-1.32 ± 0.29^{c}	18.23 ± 3.17^{cd}
11	71.51 ± 1.29^{e}	-1.52 ± 0.53^{e}	-8.17 ± 1.31^{e}	20.55 ± 2.67^{a}	54.09 ± 2.36^{c}	-3.48 ± 1.68^{g}	-15.45 ± 1.18^{e}	51.28 ± 2.97^{ab}	44.96 ± 1.67^{cd}	-3.80 ± 1.65^{f}	-14.91 ± 0.91^{f}	58.44 ± 3.35^{a}
12	74.51 ± 2.32^{bcd}	-0.88 ± 1.27^{e}	-5.18 ± 2.38^{d}	20.30 ± 1.68^{a}	52.86 ± 2.39^{cd}	-4.26 ± 0.53^{g}	-12.22± 2.23^{d}	50.59 ± 3.26^{b}	47.25 ± 3.15^{bc}	-5.10 ± 0.32^{f}	-11.57± 1.01^{e}	59.30 ± 3.32^{a}
13	80.79 ± 1.31^{a}	1.53 ± 0.76^{e}	3.67 ± 2.55^{a}	22.06 ± 2.33^{a}	71.24 ± 1.93^{a}	-0.44 ± 1.27^{f}	10.60 ± 2.77^{a}	55.44 ± 1.04^{a}	66.52 ± 2.75^{a}	-2.31 ± 0.25^{f}	12.05 ± 1.79^{a}	63.99 ± 3.46^{a}
Control	65.35 ± 1.27^{f}	16.58 ± 2.44^{b}	-0.70 ± 0.98^{b}	0.00 -	35.82 ± 1.40^{h}	41.20 ± 2.17^{b}	1.64 ± 1.65^{b}	0.00	27.34 ± 1.62^{g}	47.80 ± 1.74^{b}	6.01 ± 1.38^{b}	0.00

Note: PC0 is porang glucomannan- sodium alginate with no purple corn extract; PC1 is porang glucomannan- sodium alginate with 10% purple corn extract; PC2 is porang glucomannan- sodium alginate with 30% purple corn extract; and PC3 is porang glucomannan- sodium alginate with 50% purple corn extract. Data in the form of mean values ± standard deviation and different letter marks on different lines indicate a significant difference.

3.1.11 pH sensitivity

The sensitivity of the smart bioplastic to buffer solutions with different pH levels (1 to 13) shows a significant colour change. At pH 1, the smart bioplastic changes colour from purple to pink, indicating a response to highly acidic conditions. In the pH range of 2 to 10, the smart bioplastic did not show any noticeable colour change and remained purple, indicating colour stability in mildly acidic to neutral conditions. When the pH of the solution increased to 11 and 12, the smart bioplastic began to change colour to blue, indicating a response to alkaline conditions. Further colour changes are observed at pH 13, where the smart bioplastic turns yellowish, showing a more noticeable colour transition in highly alkaline conditions. The results of observing the colour change of the smart bioplastic in buffer solutions with pH 1 to 13 are shown visually in Figure 3.

Based on the results of statistical tests and further tests, the colour change (*ΔE**) in the PC1, PC2, and PC3 smart bioplastic s showed significant differences ($p < 0.05$) against buffer solutions with pH values ranging from 1 to 13 (Table 3). The PC1 smart bioplastic showed the highest *ΔE** value of 22.06 at pH 13, which was associated with a colour change towards pale yellow in highly alkaline conditions. The *ΔE** value at pH 1 was 20.63, indicating a significant colour shift towards pink in highly acidic conditions. Meanwhile, in the pH range of 2–10, the *ΔE** value ranged from 10.64 to 14.51, with the bioplastic colour tending to be stable in purple, indicating a subtle colour change. The *ΔE** value increased again at pH 11 and 12 with a range of 20.30-20.55, which was associated with a colour change towards greenish blue.

The PC2 smart bioplastic also shows significant colour changes, especially at extreme pH levels. The highest *ΔE** value is 55.44 at pH 13, indicating a colour change from purple to yellowish. At pH 1, the *ΔE** value is 19.15 with a pink colour. At pH 2–10, the *ΔE** value is relatively low, ranging from 9.43 to 27.16, indicating that the bioplastic colour remains in the purple spectrum. Significant changes reappear at pH 11 and 12 (*ΔE** 50.59-51.28), leading to a colour change to blue-green.

The PC3 smart bioplastic shows the most intense colour response among the three. The highest *ΔE** value is observed at pH 13 at 63.99, followed by 59.30 and 58.44 at pH 12 and 11, respectively, which illustrate a sharp colour change from blue to dark yellow. The *ΔE** value at pH 1, which is 14.50, indicates an initial colour change to pink. Meanwhile, at pH 2–10, *ΔE** ranges from 14.80 to 28.13, with a consistent colour trend from purple to bluish. The drastic increase in *ΔE** at alkaline pH indicates the high sensitivity of the PC3 smart bioplastic to alkaline environments. Overall, the three types of smart bioplastics show consistent colour change patterns: red or pink at very acidic pH (pH 1), stable purple at pH 2–10, blue-green at pH 11–12, and dark yellow at pH 13. The sharp colour change under extreme conditions demonstrates the bioplastic's effectiveness as a responsive visual pH indicator. Colour differences with *ΔE** values greater than 3 are generally considered visually perceptible to the human eye. Therefore, the *ΔE** values obtained in this study indicate that the colour changes of the indicator bioplastic could be visually distinguished under several tested pH conditions.

3.1.12 Ammonia sensitivity

The response of the smart bioplastic to ammonia vapour over 24 minutes is shown in Figure 3. The smart bioplastic initially turns purple and shows a noticeable change after exposure to ammonia vapour, gradually turning dark blue as exposure continues. The PC1 smart bioplastic showed the lowest sensitivity to ammonia vapour, with a peak of 12.39% at the 20th minute, then decreasing to 9.59% at the 24th minute.

The PC2 smart bioplastic showed a faster and stronger response, with a sensitivity of 14.63% at the 4th minute, gradually increasing to reach a peak sensitivity of 29.39% at the 20th minute, and remaining stable until the end of the observation period. The PC3 smart bioplastic showed the highest sensitivity to ammonia vapour. Its sensitivity reached 30%, then increased significantly to exceed 34.98% at minute 24th. The colour change in the PC3 bioplastic was also the most significant, indicating that the greater the concentration of added extract, the faster and stronger the response to ammonia vapour.

3.2 Discussion

3.2.1 Total anthocyanin content of purple corn extract

The porang glucomannan-alginate-based smart bioplastic, with the addition of purple corn extract, in this study, can be used as a freshness indicator for marine products, such as vannamei shrimp. In this study, the total anthocyanin content in purple corn extract was measured, which is a natural pigment that can change colour according to the pH value in solution [25]. The total anthocyanin content in purple corn extract was calculated to be 257.15 mg/L based on the cyanidin-3-glucoside content. This value is higher than the anthocyanin extract from butterfly pea flowers, which ranges from 90.9 mg/L to 143.49 mg/L [26], sweet potato extract at 253.15 mg/L [15], and jamblang fruit at 236.3 mg/L [19]. The anthocyanin content also affects the visual response of the smart bioplastic to pH changes. This can occur because anthocyanins undergo significant molecular structure changes depending on the acid-base level of the environment [27]. It should be noted that the incorporation of purple corn extract increased not only the anthocyanin content but also introduced additional aqueous components into the bioplastic-forming solution, following the formulation approach reported by Abdillah et al. [1]. Therefore, the observed changes in bioplastic properties may result from the combined effects of anthocyanins and other soluble constituents present in the extract. Further studies employing volume-adjusted controls are required to distinguish these individual contributions.

3.2.2 Visual and colour appearance

Smart bioplastic with the addition of purple corn extract has a transparent appearance and a level of colour homogeneity that indicates uniform distribution of pigments. Bubbles formed on the smart bioplastic indicator are caused by air trapped during mixing and interactions between polysaccharides and phenolic compounds. These interactions increase the viscosity of the solution, making it difficult for air to escape and causing small bubbles to form in the bioplastic matrix [28]. The level of transparency and colour homogeneity in smart bioplastics can also be influenced by the addition of purple corn extract. This is supported by Zhang et al. [3], which states that the addition of phenolic compounds to the bioplastic matrix can increase the opacity and colour stability of the bioplastic.

Changes in visual characteristics due to the addition of purple corn extract are also reflected in the colour parameters of the smart bioplastic. Colour is one of the important indicators in assessing the visual quality of the bioplastic [29]. The increase in ΔE^* value in the smart bioplastic indicates a decrease in transparency related to the natural colour intensity of anthocyanins in the film matrix [1]. This colour value is similar to that found in the study by Supeni et al. [30] on the production of sodium alginate/pectin/cellulose nanofibril bioplastics containing anthocyanins from black soybean skins. The colour values obtained in that study were the same, namely a decrease in brightness (L^*), an increase in redness (a^*), blueness (b^*), and total colour difference (ΔE^*). According to him, this occurs when anthocyanin is added to a film matrix containing polysaccharides, and as the amount increases, the natural colour of the polysaccharides becomes invisible or covered.

3.2.3 Thickness and opacity

Thickness is a very important parameter in smart bioplastics because the thickness of the bioplastic affects the physical, mechanical, and durability properties of other smart bioplastics [22]. Thickness can affect water vapour permeability; the thicker the smart bioplastic, the lower its water vapour permeability, thereby protecting the product. Conversely, the thinner the smart bioplastic, the greater its water vapour permeability [31]. Thickness can also affect the tensile strength of smart bioplastics, so the thicker the bioplastic, the greater the tensile strength, but the lower the elongation value [32].

Based on the thickness test results, it was found that the thickness of the smart bioplastic increased with increasing concentrations of purple corn extract. This was supported by research conducted by Guclu et al. [13], which stated that adding purple corn extract to chitosan smart bioplastics could increase thickness in line with the concentration of extract used. This is because the thickness of a bioplastic is influenced by the amount of solids in the solution used, the volume of the solution, and the area of the mould used in bioplastic production [33]. According to Li et al. [34], increasing the concentration of the extract will increase the polymer that makes up the bioplastic matrix, along with an increase in total volume, thereby causing an increase in the smart bioplastic. Food packaging classified as bioplastic generally has a thickness of around 0.050 to 0.250 mm and is used to wrap food products, made into bags or pouches, and applied between layers of food ingredients [35]. Thus, it can be concluded that the thickness of the bioplastic produced in this study is still within the commonly used range.

The thickness of the smart bioplastic also affects transparency. Transparency testing in this study used an opacity test, which indicates how much visible light is absorbed by a material. The higher the intensity of light that penetrates the bioplastic, the greater the transparency of the bioplastic and the lower its opacity [1]. In smart bioplastics made from alginate-porang flour, opacity increased with the addition of purple corn extract concentration. This increase indicates that the bioplastic has good light filtering capabilities, thus supporting its performance as a visual indicator.

The opacity value is in accordance with the research of Dwiyanti et al. [21], where the smart bioplastic from gellan gum-potato starch with the addition of red cabbage extract as anthocyanin will increase the opacity as the extract concentration increases. These results are in accordance with the research of Abdillah et al. [1], which stated that the addition of Kyoho grape skin extract to the halochromic smart bioplastic from arrowroot starch and iota-carrageenan can increase the opacity. This is because the opacity of a bioplastic can increase due to increased intermolecular interactions that cause greater light dispersion [21]. In this case, the addition of purple corn extract can cause co-pigmentation with the alginate-porang flour smart bioplastic, which produces a more complex molecular structure and increases light scattering in the bioplastic. As a result, the amount of light that can pass through the bioplastic is reduced, so its opacity increases.

3.2.4 Tensile strength and elongation at break

The physical characteristics of smart bioplastics are influenced by mechanical properties, particularly tensile strength and elongation at break, which serve as key indicators in assessing their effectiveness as active packaging materials. Tensile strength and elongation at break are the most frequently analysed parameters in packaging materials [12]. Tensile strength describes the maximum pressure that a material can withstand before breaking, while elongation at break indicates the extent to which a material can stretch before ultimately failing structurally [36]. These two parameters are important in determining the quality and durability of packaging materials, especially in applications that require flexibility and optimal mechanical strength.

The tensile strength of smart bioplastics increases with the addition of purple corn extract concentration. These results are in line with Qin et al. [29], who reported that the addition of purple sweet potato anthocyanin extract to carboxymethyl cellulose/starch bioplastics increased tensile strength as the extract concentration increased. The increase in tensile strength may be attributed to interactions between anthocyanin compounds and the polymer matrix, which potentially improved the structural integrity of the bioplastic. However, specific interaction mechanisms were not directly investigated in the present study [29]. The tensile strength values obtained in this study ranged from 5.28 to 7.43 MPa. According to Peralta et al. [37], the good mechanical tensile strength of a bioplastic has a range of 10–100 MPa. Thus, smart bioplastics made from porang flour and alginate with the addition of purple corn extract show mechanical characteristics that are still below this range, so they do not fully meet the criteria.

Tensile strength measurements on the smart bioplastic were followed by an elongation test, which aimed to determine how far the bioplastic could stretch to its maximum before breaking during the testing process. The elongation at break value of the smart bioplastic showed an increase with the addition of purple corn extract. The increase in break elongation values is in line with the findings of Li et al. [34], which show that the addition of purple carrot skin anthocyanin extract to starch-pectin bioplastics increases the elasticity of the bioplastics. According to the study, this is due to the possibility of sugar in the extract contributing to the plasticising action on the polymer matrix, which can increase break elongation. Bioplastics with high elongation at break are generally more flexible, which can improve their ability to form an effective barrier against external environmental factors that contribute to food spoilage. The elongation at break values obtained in this study ranged from 38.70 to 65.39%. Thus, smart bioplastics made from porang flour and alginate with the addition of purple corn extract have mechanical characteristics that support their function as active packaging.

3.2.5 Moisture content and water solubility

Physical characteristics such as water content and water solubility play an important role in determining the stability, durability, and effectiveness of smart bioplastics in food packaging applications. The water content of composite bioplastics is an important parameter for applications in the food industry because it can affect the texture, stability, and shelf life of packaged products [38]. Moisture content measurement is performed to assess how well the physical structure of the polymer bioplastic remains stable when exposed to liquids or food products with high water content [30]. Moisture content is closely related to the hydrophobicity of the bioplastic, because the higher the bioplastic's ability to repel water (hydrophobic), the less water it absorbs, making the bioplastic structure more resistant to degradation or softening due to moisture [39].

The water content value of the smart bioplastic showed an increase when purple corn extract was added. This value differs from that in the study by Supeni et al. [30] on sodium alginate/pectin/cellulose nanofibril-based bioplastics with anthocyanins from black soybean skins. According to the study, the decrease in water content occurred because the hydroxyl and carboxyl groups in phenolic compounds strengthened the intermolecular bonds in the bioplastic, making it more difficult for water to bind to polysaccharides. In contrast to the results of this study, which showed an increase, this was likely due to the presence of free anthocyanins that disrupted the density of the bioplastic structure, allowing water molecules to more easily enter the matrix network [38]. The moisture content values obtained in this study ranged from 18.98 to 29.59%. According to the SNI 06-3735-1995 standard, the maximum water content of smart bioplastics is 16%. Thus, the water content of the smart bioplastics produced in this study exceeded the specified limit, indicating that the bioplastics still tend to absorb moisture at a fairly high rate.

As interrelated parameters, water solubility tests are also important to support the interpretation of water content in smart bioplastics. Water solubility reflects the bioplastic's resistance to water exposure and its ability to maintain structural integrity when in a wet environment [13]. Water solubility is also closely related to the hydrophobicity of the bioplastic, because the higher the bioplastic's ability to repel water (hydrophobicity), the less likely it is to break down or dissolve. A high solubility value indicates that the bioplastic is more easily decomposed or damaged when exposed to moisture [4]. This study showed good results, with an increase in water solubility corresponding to the addition of purple corn extract. Although its hydrophilicity increased, this indicates potential for application as active packaging.

The addition of purple corn extract in the ANOVA showed no significant effect on the water solubility value of smart halochromic bioplastics ($p > 0.05$). However, the value of water solubility showed an increase when adding purple corn extract, with a value of 50.53 to 60.18%. This value is in line with the results of Yi et al. [38], who reported an increase in water solubility in alginate smart bioplastics with the addition of casein-carboxymethyl cellulose nanocomplexes containing anthocyanins. A similar finding was also found in the study of Supeni et al. [30] on sodium alginate/pectin/cellulose nanofibril bioplastics with anthocyanins from black soybean seed coats. The increase in water solubility was caused by the addition of anthocyanins and glycerol as plasticisers, which strengthened the bioplastic matrix but simultaneously increased the hydrophilic properties. This stimulated the sensitivity of the biopolymer bioplastic to water [38].

3.2.6 Water vapour permeability

The ability of a smart bioplastic to function effectively as an active packaging material is significantly influenced by its water vapour barrier properties, as reflected in its water vapour permeability value. Water vapour permeability is an important parameter in evaluating a bioplastic's ability to act as a water vapour barrier [38]. Low water vapour permeability is a primary target in food packaging development to enhance its water vapour barrier properties. However, in some cases, higher water vapour permeability can be utilized as an indicator in certain packaging applications. This supports the interaction between the environment and the indicator in the bioplastic, allowing for optimal colour response to changes in pH or product freshness [31].

The water vapour permeability value of smart bioplastic increases with increasing concentration of purple corn extract. The increase in water vapour permeability due to the addition of anthocyanin extract is in line with the results of Matheus et al. [31], which showed that *Arnebia euchroma* root extract increases bioplastic permeability along with increasing extract concentration. According to the study, the increase is caused by an increase in permeation pathways, which is likely caused by filler agglomeration at higher anthocyanin extract concentrations. The results of this study indicate that the increase in water vapour permeability in smart bioplastic is caused by the uneven distribution of purple corn extract, which causes the bioplastic structure to become more open and tends to be hydrophilic. The water vapour permeability value obtained in this study ranges from 0.239 to 0.288 $g{\cdot}mm/m^2{\cdot}kPa{\cdot}h$. According to Peralta et al. [37], the good water vapour permeability value of the bioplastic has a value in the range ($0.1 - 1\ g{\cdot}mm/m^2{\cdot}kPa{\cdot}h$). Thus, the water vapour permeability value of the smart bioplastic in this study is still within the recommended standard range, thus indicating a fairly good barrier ability against water vapour.

3.2.7 Swelling index

As part of its moisture barrier properties, the swelling index plays a role in determining the stability and performance of smart bioplastics. The swelling index is a crucial factor in smart packaging development because it can influence the effectiveness of the colour response on labels [14]. A high swelling value indicates a material with a high affinity for water, allowing it to absorb and expand more [3]. The higher the swelling ability, the faster the dye release occurs, which can reduce the accuracy and stability of the indicator colour change [40].

The swelling index value of smart bioplastics decreased with increasing concentration of purple corn extract. This is in line with the findings of da Silva Filipini et al. [14], which showed that the addition of red radish anthocyanins to chitosan-based smart bioplastics. A similar decrease was also found in this study [31], where the addition of *Arnebia euchroma* root extract to the colorimetric indicator reduced bioplastic swelling. The decrease in swelling index may be associated with stronger intermolecular interactions between glucomannan, alginate, and anthocyanin compounds, which could contribute to a denser bioplastic structure. Similar observations have been reported in anthocyanin-incorporated polysaccharide films [1, 14, 38].

3.2.8 Water contact angle

The barrier characteristics of a bioplastic against water are not only determined by the swelling index, but also by its surface properties, which can be measured through the water contact angle. The water contact angle is used to assess the surface properties of the bioplastic, especially in determining whether the bioplastic is hydrophilic or hydrophobic. The smaller the contact angle, the higher the hydrophilic properties, while a larger angle indicates hydrophobic properties because the surface tends to repel water [14]. According to Matheus et al. [31], surfaces with a contact angle value of less than 65° are categorised as hydrophilic, while a water contact angle value of more than 65° indicates hydrophobic characteristics.

The water contact angle value of the smart bioplastic decreased with increasing concentration of purple corn extract. Based on this, the resulting smart bioplastic has hydrophilic properties. The decrease that occurred due to the addition of the extract is in line with the findings of Li et al. [34], who showed a decrease in the water contact angle on starch-pectin smart labels with purple carrot peel anthocyanins. According to the study, this decrease occurred due to the presence of water-soluble components on the bioplastic surface, such as the intrinsic hydroxyl (-OH) groups of starch and glycerol added as a plasticiser. The presence of these polar groups allows for strong interactions with water molecules through the formation of hydrogen bonds, thereby increasing the bioplastic's affinity for water.

The relatively high moisture content (18.98–29.59%), high water solubility (50.53–60.18%), and low water contact angle values (31.41–43.31°) indicate that the developed bioplastics possess a predominantly hydrophilic character. These properties may limit their application as standalone packaging materials or direct-contact bioplastics for high-moisture foods. Nevertheless, such characteristics do not preclude their use as intelligent indicator labels positioned inside packaging systems without direct contact with the food product. In this configuration, the bioplastic can respond to spoilage-related volatile compounds while minimizing structural degradation caused by moisture exposure.

3.2.9 pH sensitivity

Smart bioplastics containing purple corn extract were subjected to colour change tests at pH 1 to 13 to identify their potential use as freshness indicators for food products. Based on sensitivity tests to buffer solutions with varying pH values (1 to 13), the smart bioplastic exhibited significant colour changes. At very acidic pH (pH 1), the bioplastic changed colour from purple to pink due to the formation of a cationic flavylium structure resulting from an increase in the number of methoxy groups [41]. However, in the pH range of 2 to 10, the colour change was not visually significant, indicating the stability of the anthocyanin colour. This is due to the balance between the flavylium and quinoidal forms, resulting in a stable purple colour [42].

As the pH increases from pH 11 to 13, a gradual colour change occurs from blue-green to yellow, with a significant ΔE^* value, especially in the PC3 smart bioplastic. The colour changes observed under different pH conditions are consistent with the known structural transformations of anthocyanins reported in the literature, including transitions among flavylium, quinoidal, and chalcone forms [41-43]. The highest colour change response at extreme pH is shown by the smart bioplastic with the addition of 50% extract (PC3), which has a stronger potential for use as a pH indicator in food products such as white-legged shrimp.

Research by Wahyuningsih et al. [19] utilising jamblang peel extract in methylcellulose bioplastics demonstrated high potential in detecting food spoilage characterised by pH changes. Furthermore, Liu et al. [44] reported that a smart bioplastic based on konjac glucomannan and chitin nanocrystals with the addition of purple cabbage extract also demonstrated potential as intelligent packaging capable of detecting food freshness. Anthocyanins have high potential as sensors due to their sensitivity to pH changes, so they can be used to detect compounds resulting from food degradation, such as volatile nitrogen compounds, which are alkaline and usually cause an increase in pH in products such as fish [45]. This strengthens the findings in this study that the high anthocyanin content in purple corn extract plays a significant role as a freshness indicator for perishable products such as fish, meat, and other seafood.

Although the most pronounced colour transitions were observed under strongly acidic and alkaline conditions, gradual colour changes were also detected within the neutral-to-alkaline range. Since seafood spoilage is generally associated with moderate increases in pH rather than extreme pH conditions, further studies focusing on narrower pH intervals relevant to seafood deterioration (e.g., pH 6–10) are required to evaluate the practical sensitivity of the developed bioplastic under real storage conditions.

3.2.10 Ammonia sensitivity

The ammonia sensitivity test was conducted as a preliminary evaluation of the bioplastic response toward alkaline volatile compounds. Although the applied ammonia concentration was higher than that typically generated during seafood spoilage, the results demonstrate the potential responsiveness of the developed bioplastic to basic vapours. Further validation under real food storage conditions is required to confirm its practical applicability as a freshness indicator. The colour change that occurs due to the transformation of the anthocyanin molecular structure under various pH conditions allows this smart bioplastic to detect basic volatile compounds such as ammonia [46]. Therefore, the sensitivity of the bioplastic to ammonia vapour exposure was tested. The results showed that the smart bioplastic underwent a significant colour change, from purple to dark blue, in response to ammonia vapour exposure. This colour change is caused by the interaction between anthocyanin molecules and basic compounds such as ammonia, which induces changes in the chemical structure of the anthocyanin [47]. Increasing the concentration of purple corn extract containing anthocyanins affected the sensitivity of the smart bioplastic to ammonia vapour exposure by increasing the intensity of the colour change.

The smart bioplastic with 50% extract added (PC3) showed the highest sensitivity to ammonia vapour, reaching 34.98% sensitivity at 24 minutes. The bioplastic also experienced a significant increase in the first 4 minutes, indicating that this smart bioplastic has a high and rapid response to ammonia vapour. This is consistent with research by Tavakoli et al. [47] that anthocyanins from blue dawn flowers and purple cabbage in smart bioplastic s showed high and rapid sensitivity when exposed to ammonia vapour. Furthermore, research [48] showed that anthocyanins from red cabbage have a high sensitivity value to ammonia vapour, namely 50%. Therefore, this colour change indicates that the smart bioplastic based on purple corn extract is capable of detecting volatile compounds, such as the presence of ammonia vapour produced by perishable products.

The observed color changes in response to ammonia exposure are consistent with the pH-responsive behavior of anthocyanins reported in previous studies. Although several mechanisms, including intermolecular interactions within the polymer matrix and anthocyanin structural transformations, have been proposed to explain the observed changes in bioplastic properties, these interpretations are based on previous literature. Structural characterization techniques such as Fourier-transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), X-ray diffraction (XRD), or thermal analyses were not performed in the present study. Therefore, further studies employing these techniques are required to provide direct evidence supporting the proposed mechanisms.

The present study utilized porang glucomannan, sodium alginate, and purple corn extract, which are derived from renewable natural resources and are widely considered promising materials for the development of bio-based packaging systems. However, the sustainability of the developed bioplastic was not directly evaluated, as biodegradation behavior, migration safety, food-contact safety, environmental impact, and end-of-life performance were beyond the scope of this study. Therefore, while the developed bioplastic demonstrates promising functional properties as a pH-responsive indicator material, further investigations are required to verify its environmental sustainability and safety for practical food packaging applications.

4. CONCLUSION

The incorporation of purple corn extract significantly affected the physicochemical properties of the smart bioplastic films. The developed films exhibited thickness values of 0.146–0.171 mm, tensile strength of 5.28–7.43 MPa, elongation at break of 38.70–65.39%, water vapour permeability of 0.239–0.288 g·mm/m²·h·kPa, water solubility of 50.53–60.18%, swelling index of 7.17–12.04%, and water contact angle of 31.41–43.31°. Purple corn extract also enhanced the color responsiveness of the films toward pH and ammonia exposure. Among the tested formulations, PC2 showed the most balanced physicochemical properties, whereas PC3 exhibited the strongest color response. These findings demonstrate the potential of porang glucomannan–alginate films containing purple corn extract as pH-responsive smart indicator materials. The developed smart bioplastic demonstrated promising optical, physical, mechanical, and indicator properties, particularly in response to pH changes and ammonia vapour. These findings suggest its potential application as a visual freshness indicator for food packaging systems. Nevertheless, the present study represents a preliminary characterization and indicator-response evaluation. Future research should validate the film under actual food storage conditions, particularly during refrigerated storage of shrimp product, by monitoring freshness indicators such as TVB-N, pH, microbial growth (TVC), and sensory quality to confirm its practical performance.

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REFERENCES

[1] Abdillah, A.A., Lin, H.H., Charles, A.L. (2022). Development of halochromic indicator film based on arrowroot starch/iota-carrageenan using Kyoho skin extract to monitor shrimp freshness. International Journal of Biological Macromolecules, 211: 316-327. https://doi.org/10.1016/j.ijbiomac.2022.05.076

[2] Mussagy, C.U., Oliveira, G., Ahmad, M., Mustafa, A., Herculano, R.D., Farias, F.O. (2024). Halochromic properties of carotenoid-based films for smart food packaging. Food Packaging and Shelf Life, 44: 101325. https://doi.org/10.1016/j.fpsl.2024.101325

[3] Zhang, J., Liu, S., Xie, C., Wang, C., Zhong, Y., Fan, K. (2024). Recent advances in pH-sensitive indicator films based on natural colorants for smart monitoring of food freshness: A review. Critical Reviews in Food Science and Nutrition, 64(33): 12800-12819. https://doi.org/10.1080/10408398.2023.2257327

[4] Nurhayati, T., Jacoeb, A.M., Utari, S.A., Azizah, L.H., Hidayat, T. (2018). Quality assessment of vannamei shrimp from Indonesian waters: Quality assessment of vannamei shrimp. Proceedings of the Pakistan Academy of Sciences: B. Life and Environmental Sciences, 55(1): 21-28. https://ppaspk.org/index.php/PPAS-B/article/view/210.

[5] Das, J., Mishra, H.N. (2023). A comprehensive review of the spoilage of shrimp and advances in various indicators/sensors for shrimp spoilage monitoring. Food Research International, 173: 113270. https://doi.org/10.1016/j.foodres.2023.113270

[6] Khezerlou, A., Alizadeh Sani, M., Tavassoli, M., Abedi-Firoozjah, R., Ehsani, A., McClements, D.J. (2023). Halochromic (pH-Responsive) indicators based on natural anthocyanins for monitoring fish freshness/spoilage. Journal of Composites Science, 7(4): 143. https://doi.org/10.3390/jcs7040143

[7] Lin, D., Sun, L.C., Chen, Y.L., Liu, G.M., Miao, S., Cao, M.J. (2022). Shrimp spoilage mechanisms and functional films/coatings used to maintain and monitor its quality during storage. Trends in Food Science & Technology, 129: 25-37. https://doi.org/10.1016/j.tifs.2022.08.020

[8] Permatasari, N.D., Witoyo, J.E., Masruri, M., Yuwono, S.S., Widjanarko, S.B. (2022). Application of a two-level full factorial design for the synthesis of composite bioplastics from durian seed flour and yellow konjac flour incorporating ethanolic extract of syzygium myrtifolium leaves and its characterization. Nature Environment & Pollution Technology, 21(4): 1893-1901. https://doi.org/10.46488/NEPT.2022.v21i04.044

[9] Kocira, A., Kozłowicz, K., Panasiewicz, K., Staniak, M., Szpunar-Krok, E., Hortyńska, P. (2021). Polysaccharides as edible films and coatings: Characteristics and influence on fruit and vegetable quality—A review. Agronomy, 11(5): 813. https://doi.org/10.3390/agronomy11050813

[10] Priyadarshi, R., Ezati, P., Rhim, J.W. (2021). Recent advances in intelligent food packaging applications using natural food colorants. ACS Food Science & Technology, 1(2): 124-138. https://doi.org/10.1021/acsfoodscitech.0c00039

[11] Nasution, H., Harahap, H., Julianti, E., Safitri, A., Jaafar, M. (2023). Smart packaging based on polylactic acid: The effects of antibacterial and antioxidant agents from natural extracts on physical–mechanical properties, colony reduction, perishable food shelf life, and future prospective. Polymers, 15(20): 4103. https://doi.org/10.3390/polym15204103

[12] Alizadeh-Sani, M., Mohammadian, E., Rhim, J.W., Jafari, S.M. (2020). pH-sensitive (halochromic) smart packaging films based on natural food colorants for the monitoring of food quality and safety. Trends in Food Science & Technology, 105: 93-144. https://doi.org/10.1016/j.tifs.2020.08.014

[13] Guclu, G., Dagli, M.M., Aksay, O., Keskin, M., Kelebek, H., Selli, S. (2023). Comparative elucidation on the phenolic fingerprint, sugars and antioxidant activity of white, orange and purple-fleshed sweet potatoes (Ipomoea batatas L.) as affected by different cooking methods. Heliyon, 9(8): e18684. https://doi.org/10.1016/j.heliyon.2023.e18684

[14] da Silva Filipini, G., Romani, V.P., Martins, V.G. (2020). Biodegradable and active-intelligent films based on methylcellulose and jambolão (Syzygium cumini) skins extract for food packaging. Food Hydrocolloids, 109: 106139. https://doi.org/10.1016/j.foodhyd.2020.106139

[15] Zhang, C., Sun, G., Cao, L., Wang, L. (2020). Accurately intelligent film made from sodium carboxymethyl starch/κ-carrageenan reinforced by mulberry anthocyanins as an indicator. Food Hydrocolloids, 108: 106012. https://doi.org/10.1016/j.foodhyd.2020.106012

[16] Zhan, S., Chen, X., Luan, X., Feng, Y., Song, L., Han, X., Liu, Z. (2025). A highly stable gellan gum/potato starch/anthocyanin smart film with ferulic acid co-pigmentation for monitoring fish freshness. International Journal of Biological Macromolecules, 288: 138763. https://doi.org/10.1016/j.ijbiomac.2024.138763

[17] Rusli, A., Santi, A., Malle, S., Arfini, F., Arsyad, M.A., Syukroni, I., Inthe, M.G. (2024). Application of antimicrobial edible film incorporated with Caulerpa racemosa crude extract as active packaging of seaweed dodol. Applied Food Research, 4(2): 100625. https://doi.org/10.1016/j.afres.2024.100625

[18] Abdillah, A.A., Lee, R.C., Charles, A.L. (2024). Improving physicomechanical properties of arrowroot starch films incorporated with kappa-carrageenan: Sweet cherry coating application. International Journal of Biological Macromolecules, 277: 133938. https://doi.org/10.1016/j.ijbiomac.2024.133938

[19] Wahyuningsih, S., Wulandari, L., Wartono, M.W., Munawaroh, H., Ramelan, A.H. (2017). The effect of pH and color stability of anthocyanin on food colorant. IOP Conference Series: Materials Science and Engineering, 193(1): 012047. https://doi.org/10.1088/1757-899X/193/1/012047

[20] Pham, T.N., Lam, T.D., Nguyen, M.T., Le, X.T., Vo, D.V.N., Toan, T.Q., Vo, T.S. (2019). Effect of various factors on extraction efficiency of total anthocyanins from Butterfly pea (Clitoria ternatea L. Flowers) in Southern Vietnam. IOP Conference Series: Materials Science and Engineering, 544(1): 012013. https://doi.org/10.1088/1757-899X/544/1/012013

[21] Dwiyanti, G., Siswaningsih, W., Febrianti, A. (2018). Production of purple sweet potato (Ipomoea batatas L.)

juice having high anthocyanin content and antioxidant activity. Journal of Physics: Conference Series, 1013(1): 012194. https://doi.org/10.1088/1742-6596/1013/1/012194

[22] Yang, Y., Chen, L., Chen, M., Liu, F., Zhong, F. (2025). Interactions between rice protein and anthocyanin with different pH-cycle: Structural characterization, binding mechanism and stability. Food Hydrocolloids, 165: 111230. https://doi.org/10.1016/j.foodhyd.2025.111230

[23] Pan, J., Li, C., Liu, J., Jiao, Z., et al. (2024). Polysaccharide-based packaging coatings and films with phenolic compounds in preservation of fruits and vegetables—A review. Foods, 13(23): 3896. https://doi.org/10.3390/foods13233896

[24] Zhan, S., Yi, F., Hou, F., Song, L., et al. (2024). Development of pH-freshness smart label based on gellan gum film incorporated with red cabbage anthocyanins extract and its application in postharvest mushroom. Colloids and Surfaces B: Biointerfaces, 236: 113830. https://doi.org/10.1016/j.colsurfb.2024.113830

[25] Jiang, G., Hou, X., Zeng, X., Zhang, C., et al. (2020). Preparation and characterization of indicator films from carboxymethyl-cellulose/starch and purple sweet potato (Ipomoea batatas (L.) lam) anthocyanins for monitoring fish freshness. International Journal of Biological Macromolecules, 143: 359-372. https://doi.org/10.1016/j.ijbiomac.2019.12.024

[26] Wang, S., Han, X., Chen, Y., Shao, Y., et al. (2025). Preparation of sodium alginate/pectin/cellulose nanofibrils films containing black soybean seed coat anthocyanins for monitoring goat meat freshness. Food Control, 171: 111096. https://doi.org/10.1016/j.foodcont.2024.111096

[27] Huang, S., Xiong, Y., Zou, Y., Dong, Q., Ding, F., Liu, X., Li, H. (2019). A novel colorimetric indicator based on agar incorporated with Arnebia euchroma root extracts for monitoring fish freshness. Food Hydrocolloids, 90: 198-205. https://doi.org/10.1016/j.foodhyd.2018.12.009

[28] Siskawardani, D.D., Warkoyo, Hidayat, R., Sukardi. (2020). Physic-mechanical properties of edible film based on taro starch (Colocasia esculenta L. Schoott) with glycerol addition. IOP Conference Series: Earth and Environmental Science, 458(1): 012039. https://doi.org/10.1088/1755-1315/458/1/012039

[29] Qin, Y., Liu, Y., Yuan, L., Yong, H., Liu, J. (2019). Preparation and characterization of antioxidant, antimicrobial and pH-sensitive films based on chitosan, silver nanoparticles and purple corn extract. Food Hydrocolloids, 96: 102-111. https://doi.org/10.1016/j.foodhyd.2019.05.017

[30] Supeni, G., Cahyaningtyas, A.A., Fitrina, A. (2015). Characterization of the physical and mechanical properties of chitosan addition to modified carrageenan and tapioca edible films. Jurnal Kimia dan Kemasan, 37(2): 103-110. https://www.neliti.com/publications/107331/karakterisasi-sifat-fisik-dan-mekanik-penambahan-kitosan-pada-edible-film-karage.

[31] Matheus, J.R.V., Maragoni-Santos, C., de Freitas, T.F., Hackbart, E.F.C., et al. (2024). Starch-pectin smart tag containing purple carrot peel anthocyanins as a potential indicator of analogous meat freshness. International Journal of Biological Macromolecules, 283: 137161. https://doi.org/10.1016/j.ijbiomac.2024.137161

[32] Hamed, I., Jakobsen, A.N., Lerfall, J. (2022). Sustainable edible packaging systems based on active compounds from food processing byproducts: A review. Comprehensive Reviews in Food Science and Food Safety, 21(1): 198-226. https://doi.org/10.1111/1541-4337.12870

[33] Thakur, R., Saberi, B., Pristijono, P., Golding, J., et al. (2016). Characterization of rice starch-ι-carrageenan biodegradable edible film. Effect of stearic acid on the film properties. International Journal of Biological Macromolecules, 93: 952-960. https://doi.org/10.1016/j.ijbiomac.2016.09.053

[34] Li, H., Wang, Z., Zhu, F., Li, G. (2024). Alginate-based active and intelligent packaging: Preparation, properties, and applications. International Journal of Biological Macromolecules, 279: 135441. https://doi.org/10.1016/j.ijbiomac.2024.135441

[35] Han, J.H. (2014). Edible films and coatings: A review. In Innovations in Food Packaging, pp. 213-255. https://doi.org/10.1016/B978-0-12-394601-0.00009-6

[36] Rashid, A., Qayum, A., Bacha, S.A.S., Liang, Q., et al. (2024). Novel pullulan-sodium alginate film incorporated with anthocyanin-loaded casein-carboxy methyl cellulose nanocomplex for real-time fish and shrimp freshness monitoring. Food Hydrocolloids, 156: 110356. https://doi.org/10.1016/j.foodhyd.2024.110356

[37] Peralta, J., Bitencourt-Cervi, C.M., Maciel, V.B., Yoshida, C.M., Carvalho, R.A. (2019). Aqueous hibiscus extract as a potential natural pH indicator incorporated in natural polymeric films. Food Packaging and Shelf Life, 19: 47-55. https://doi.org/10.1016/j.fpsl.2018.11.017

[38] Yi, F., Hou, F., Zhan, S., Song, L., et al. (2023). Preparation, characterization and application of pH-responsive smart film based on chitosan/zein and red radish anthocyanin. International Journal of Biological Macromolecules, 253: 127037. https://doi.org/10.1016/j.ijbiomac.2023.127037

[39] Latiff, N.F., Shaik, M.I., Mohamad, N.J., Khairul, W.M., Daud, A.I., Nurhadi, B., Sarbon, N.M. (2025). Recent advances in green halochromic smart film packaging: Investigating the natural colorant as biosensor in smart film packaging for real-time meat freshness monitoring. Food Control, 172: 111157. https://doi.org/10.1016/j.foodcont.2025.111157

[40] Alappat, B., Alappat, J. (2020). Anthocyanin pigments: Beyond aesthetics. Molecules, 25(23): 5500. https://doi.org/10.3390/molecules25235500

[41] Mendoza, J., Pina, F. (2021). Achieving complexity at the bottom through the flavylium cation-based multistate: A comprehensive kinetic and thermodynamic study. Recent Advances in Polyphenol Research, 7: 1-23. https://doi.org/10.1002/9781119545958.ch1

[42] Pismenskaya, N., Sarapulova, V., Klevtsova, A., Mikhaylin, S., Bazinet, L. (2020). Adsorption of anthocyanins by cation and anion exchange resins with aromatic and aliphatic polymer matrices. International Journal of Molecular Sciences, 21(21): 7874. https://doi.org/10.3390/ijms21217874

[43] Wu, C., Li, Y., Sun, J., Lu, Y., et al. (2020). Novel konjac glucomannan films with oxidized chitin nanocrystals immobilized red cabbage anthocyanins for intelligent food packaging. Food Hydrocolloids, 98: 105245. https://doi.org/10.1016/j.foodhyd.2019.105245

[44] Liu, D., Zhang, C., Pu, Y., Chen, S., Liu, L., Cui, Z., Zhong, Y. (2022). Recent advances in pH-responsive freshness indicators using natural food colorants to monitor food freshness. Foods, 11(13): 1884. https://doi.org/10.3390/foods11131884

[45] Xiaowei, H., Liuzi, D., Zhihua, L., Jin, X., et al. (2023). Fabrication and characterization of colorimetric indicator for salmon freshness monitoring using agar/polyvinyl alcohol gel and anthocyanin from different plant sources. International Journal of Biological Macromolecules, 239: 124198. https://doi.org/10.1016/j.ijbiomac.2023.124198

[46] Li, R., Feng, H., Wang, S., Zhuang, D., Zhu, J. (2024). A colorimetry-enhanced tri-functional film with high stability by polyphenol-anthocyanin co-pigmentation/conjugate: New prospect for active intelligent food packaging. Food Chemistry, 447: 138927. https://doi.org/10.1016/j.foodchem.2024.138927

[47] Tavakoli, S., Mubango, E., Tian, L., ŃDri, Y.B., Tan, Y., Hong, H., Luo, Y. (2023). Novel intelligent films containing anthocyanin and phycocyanin for nondestructively tracing fish spoilage. Food Chemistry, 402: 134203. https://doi.org/10.1016/j.foodchem.2022.134203

[48] Chen, M., Yan, T., Huang, J., Zhou, Y., Hu, Y. (2021). Fabrication of halochromic smart films by immobilizing red cabbage anthocyanins into chitosan/oxidized-chitin nanocrystals composites for real-time hairtail and shrimp freshness monitoring. International Journal of Biological Macromolecules, 179: 90-100. https://doi.org/10.1016/j.ijbiomac.2021.02.170