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Characterization of edible films developed from kappa-carrageenan reinforced with *pedada* flour (*Sonneratia caseolaris*): A potential packaging application for fish fillets

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ABSTRACT

Biodegradable polymers, such as kappa-carrageenan (K), are in developed to replace petroleum-based packaging materials, but presented a fragile film. Hence, to enhance mechanical properties, a cheap polymer, such as flour from pedada fruit, could be used as a substitute material for developing packaging products. This study focused on the development of combination kappa-carrageenan (K) (2.875, 2.75, 2.5, and 2.25 %) and pedada flour (P) (0.125, 0.25, 0.5, and 0.75%) as a biodegradable edible film (K/P edible films) for food packaging, compared with kappa-carrageenan-based film (3%, as control). The edible films were characterized based on physico-mechanical and barrier properties, functional and crystallinity properties, biodegradability, and were applied as wrap packaging on fish fillet product. As a result, the increments of 0.125% and 0.25% pedada flour in K/P edible films increased tensile strength (29.92 and 33.61 MPa, respectively) compared with the control (24.69 MPa), but lower at 20.86 and 17.80 MPa after 0.5% and 0.75% additions of pedada flour. Furthermore, the wrap application of K/P edible films reduced weight loss in tilapia fillets stored at 4°C for 0, 3, and 6 days compared with the unwrapped product. These results suggested that the KP-based films are promising candidates for sustainable, effective, biodegradable packaging materials, particularly for preserving food products.

1. Introduction

Global production of plastics has surged to exceed 400 million metric tons annually and increasing by 1.6% each year (Najahi et al., 2025; Sarısaltık et al., 2025). Synthetic plastic materials are ubiquitous in daily life, particularly in food packaging to preserve the freshness of food products. However, single-use plastic packaging has created severe environmental and health challenges (Sarısaltık et al., 2025). The plastic waste from food packaging is a severe problem; since most plastic is non-biodegradable, over 75% of the 8.3 billion tons ever produced has become waste (Tejaswini et al., 2022), with global plastic waste projected to reach 33 billion metric tons by 2050 (Mielinger & Weinrich, 2024). Moreover, plastic debris can persist in the environment for over 500 years, with profound consequences for human health, socioeconomic conditions, and community structures (Chen et al., 2024; Najahi et al., 2025). Hence, to reduce the usage of non-biodegradable plastic packaging, researchers are developing sustainable packaging alternatives, including edible films or bioplastics (Sarısaltık et al., 2025).

Edible film is a thin layer, typically 0.25 mm or less, derived from renewable natural polymers. While it can mimic the properties of conventional petroleum-based plastics, and has the distinct advantage of being both biodegradable and edible (Bidari et al., 2023; Charles et al., 2022; Dang et al., 2022). Accordingly, edible films could extend product shelf life, protect against physical and mechanical damage, and act as a barrier against microbial contamination. Edible films are generally formulated from biopolymers such as polysaccharides, proteins, lipids,

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and various additives (Charles et al., 2025). However, the main challenge is to select the right combination of environmentally friendly materials to achieve optimal performance.

Polysaccharides such as kappa-carrageenan, a hydrocolloid, are excellent primary ingredients for edible films due to their strong film-forming properties (Dang et al., 2022). Kappa-carrageenan is widely used as a thickening, stabilizing, and gelling agent in various food products, including dairy, meat, and confectionery (Jabeen et al., 2025; Kalsi et al., 2025). Kappa carrageenan also presents hard and brittle characteristics causes has a double helix structure that aggregates into junction zones involving multiple polymer chains (Russo Spena & Grizzuti, 2025). Nevertheless, films made from a single polymer often have limitations, such as fragility, which can be improved by blending with other polymers (Ismawanti et al., 2020). Beyond polymer selection, the performance of edible films is influenced by several critical parameters, including plasticizer concentration, film-forming technique, processing conditions, and molecular interactions within the polymer matrix. These factors have been shown to significantly affect the physical, mechanical, and barrier properties of edible films (Bidari et al., 2023; Charles et al., 2025). Another weakness of kappa-carrageenan-based films is their lower flexibility and tend to form a brittle films (Abdillah et al., 2024). To limit the drawback, researchers combined kappa-carrageenan with other polymer sources derived from starches, including arrowroot starch (Abdillah et al., 2024), cassava starch (de Lima Barizão et al., 2020), and tapioca starch (Yap et al., 2024). Accordingly, flours processed from pea and fruit also show great promise as composite polymers for creating more robust and effective edible films (Mueller et al., 2024). Hence, the incorporation of flour as a combination polymer with kappa-carrageenan could hypothetically limit the weakness and improve the packaging properties of kappa-carrageenan-based edible films

One promising natural polymer combination for edible film production is the pedada fruit (*Sonneratia caseolaris*) flour, an abundant resource whose utilization remains limited and underexplored due to seasonal availability and short shelf life (Pradana et al., 2017). Pedada flour is used to enhance the nutritional profile of various food products and beverages, providing essential nutrients and bioactive compounds, but the application as food product is scarce (Dari & Junita, 2020; Jariyah et al., 2025; Wintah et al., 2023). Previous reports indicate that pedada flour could form an edible film, its physico-mechanical properties and water vapor barrier properties remain suboptimal (Saidi et al., 2025). While also suggests combining with other polymers to create a high-performance film. Nevertheless, to the best of our knowledge, the characterization of edible films made from kappa-carrageenan and pedada flour blends has not been reported, particularly regarding to packaging properties and the application. Therefore, this study aims to develop an edible film from a blend of kappa-carrageenan and pedada flour and were characterized based on their physicochemical and barrier properties, biodegradability, surface and cross-sectional microstructure, crystallinity, and functional properties. In addition, the edible films were applied as wrapping materials to evaluate their effectiveness in preserving the freshness of tilapia fillets during refrigerated storage. The use of tilapia fillets as an ideal model for evaluation film due to their sensitivity to humidity and post-harvest spoilage, providing industrially relevant data for sustainable preservation as a widely consumed aquatic product (Gürdal & Çetinkaya, 2024).

2. Materials and methods

2.1. Materials

Pedada fruit was collected from the Wonorejo mangrove area in Surabaya. Kappa-carrageenan with a gel strength of 1500–2000 g/cm^2, a viscosity of 200 mPa·s, and a moisture content of 12%, was purchased from local food material supplier "CV Nura Jaya" in Surabaya, Indonesia. Food-grade glycerol and distilled water, used as an additive and solvent, respectively, were obtained from a local chemical supplier in Surabaya. Fresh tilapia fillets were supplied by a culture pond at the Faculty of Fisheries and Marine of Universitas Airlangga in Surabaya, Indonesia.

2.2 Pedada flour production

Mature and fresh pedada fruit (light cream to brownish color of flesh with no black dot or fungi contamination) were harvested from the mangrove tree. Flour from pedada fruit was produced following the method of Pradana et al. (2017) with minor modifications. The fruits were first cleaned under running tap water and were peeled, then the pedada flesh was air-dried until no surface water remained. The flesh was cut into small pieces, placed on a tray, and sun-dried for three days until the moisture excess was less than 10%. The dried material was ground using a home-scale grinder (FOMAC FGD-Z100, Jakarta, Indonesia) and sieved using a 200-mesh screen to obtain a homogeneous flour with a uniform particle size. The final processed pedada flour was stored in a sealed container with silica gel at room temperature (25 ± 2°C) until film production. Based on the chemical characterization, the pedada flour contained 9.34% water, 4.26% crude protein, 1.495% crude fat, 79.24% carbohydrate, and 15.39% amylose.

2.2. Film production

The kappa-carrageenan (K) -based edible films, incorporating pedada flour (P), were fabricated using a casting method adapted from Abdillah et al. (2024), with modifications to the formulation, and according to preliminary research, the optimal carrageenan concentration is a maximum of 3%. The films were produced by mixing pedada flour and kappa-carrageenan in different composite ratios, with a pure KP0 film serving as the control (Table S1). The process began by adding pedada flour to 19.4 mL of distilled water and stirring at 400 rpm on a hot plate (Thermo Scientific, Cimarec+, Waltham, Massachusetts, USA) at 95°C for approximately 5 min until the flour dissolved. Kappa-carrageenan was gradually added to this solution to prevent aggregation. The mixed solution was continuedly stirring at 95°C for 5 min until kappa-carrageenan gelatinization was observed, then glycerol (180 μL) was added as a plasticizer and was mixed for a further 5 min. The resulting film solution (20 mL) was sonicated (ELMA S60H, Singen, Germany) at 50°C for 15 min to remove entrapped gas bubbles. The solution was then poured into acrylic mold (110 mm × 110 mm) and were dried in a convection oven (Memmert UN55, Ebermergen, Bavaria, Germany) at 45°C for 16 h. The dried kappa-carrageenan/pedada flour (K/P) edible films were stored at room temperature (25°C) contained dried silica gel to maintain humidity. A digital thermometer (HTC-1, Dongguan, Guangdong, China) was used to monitor the temperature and humidity (50%) during storage. Pedada flour production and K/P edible film production are illustrated in Fig. S1.

2.3. Physico-mechanical characterization of K/P edible films

2.3.1. Visual aspect and optical properties

The visual characteristics of K/P edible films were assessed based on physical attributes such as transparency, uniformity, ease of handling, flexibility, and the absence of surface cracks. Colorimetric properties were quantified using the CIELAB color space system with a colorimeter (LS170, Shenzhen Linshang Technology Co., Ltd., China). Color parameters were recorded for lightness (L^*), the red-green axis (a^*), and the yellow-blue axis (b^*). The total color difference (ΔE) was calculated relative to a white reference standard ($L^* = 97.39$; $a^* = 0.14$; $b^* = 1.94$) using Eq. (1).

$$\Delta E = \left[\sqrt{(\Delta L^2) + (\Delta a^2) + \Delta b^2}\right] \quad (1)$$

The opacity of the edible films samples was measured using a UV-Visible spectrophotometer (N4S UV-VIS, Drawell, Shanghai, China). Samples were cut into 50 mm × 9 mm strips, placed in a glass cuvette,

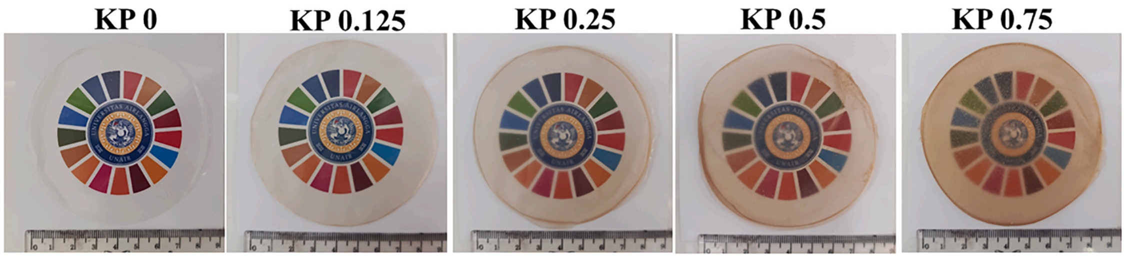

Fig. 1. Visual aspects and optical properties of K/P edible films; KP 0 (Control): Kappa-carrageenan with no pedada flour; KP 0.125: 2.875% kappa-carrageenan with 0.125% pedada flour; KP 0.25: 2.75% kappa-carrageenan with 0.25% pedada flour; KP 0.5: 2.5% kappa-carrageenan with 0.5% pedada flour; KP 0.75: 2.25% kappa-carrageenan with 0.75% pedada flour.

and their absorbance was recorded at 600 nm, with an empty cuvette serving as the blank. Opacity values were calculated using Eq. (2).

$$Opacity = \left[\frac{A_{600}}{Thickness}\right] \quad (2)$$

2.3.2. Edible films thickness

Edible film thickness was determined at ten random locations on each sample using a digital micrometer gauge (model R-219-23, Jiangxi Provincial Ruifeng Machinery & Tools Co., Ltd., China) with a precision of ±0.001 mm.

2.3.3. Tensile strength (TS) and elongation at break (EAB) of edible films

The K/P edible films were cut into 25 mm × 7 mm rectangular strips. Tensile strength (TS), elongation at break (EAB), and Young's Modulus (YM) were then measured with a universal testing machine (YZC-1B, Surabaya, Indonesia) following the method and the protocol developed by Farhan & Hani (2017). The sample (12 mm × 41 mm) was clipped using two separation grips with 30 mm of distance; the test was performed with a load cell of 400 N and a crosshead speed of 5 mm/min. TS and YM are reported in megapascals (MPa), and EAB is expressed as a percentage (%).

2.3.4. Scanning electron microscope and laser microscope analysis

To examine their microstructure, the K/P film samples were coated with a thin gold layer by vacuum sputter deposition. The surface morphology and cross-sectional structure were then analyzed using a scanning electron microscope (SEM) (Thermo Scientific Phenom ProX, Eindhoven, Nederland) at 500× magnification and an accelerating voltage of 5 kV.

2.4. Water vapor permeability

The water vapor permeability (WVP) of the edible films was measured using a gravimetric method based on Abdillah & Charles (2021). A glass cup containing 10 g of dry silica gel was sealed with a circular film sample. This assembly was stored at 25 ±2°C and 75% relative humidity (RH) and weighed using an analytical balance (OHAUS PX224, Parsippany, New Jersey, USA) with a capacity of 220 g every 24 h for 7 days. The water vapor transmission rate (WVTR) was calculated from the slope of weight gain over time using Eq. (3). The WVP was then determined with Eq. (4):

$$WVTR\left(\frac{g}{m^2.h}\right) = \left[\frac{slope}{film\ area}\right] \quad (3)$$

$$WVP\left(\frac{g.mm}{m^2.h.kPa}\right) = \left[\frac{(WVTR \times film\ thickness)}{S \times (RH_2 - RH_1)}\right] \quad (4)$$

where WVTR is the water vapor transmission rate (g/m^2h), S is the water saturation pressure (kPa) in the test chamber, RH_1 is the relative humidity of the silica gel, and RH_2 is the relative humidity of the chamber, and WVP is water vapor permeability ($g.mm/m^2$. kPa.h).

2.5. Fourier transform infrared analysis

The functional groups of the K/P edible films, pedada flour, and kappa-carrageenan were analyzed using an FTIR spectrometer (Shimadzu IRTracer-100, Kyoto, Japan). Samples were scanned from 4000 to 500 cm^{-1}, with the results expressed in transmittance (Dong et al., 2022).

2.6. X-ray diffraction analysis

The crystallinity of the K/P edible films, pedada flour, and pure kappa-carrageenan was analyzed using an X-ray diffractometer (Rigaku MiniFlex 600, Tokyo, Japan) with Cu Kα radiation operated at 40 kV and 40 mA. Scans were performed at 10°/min over a 2θ range of 5° to 40°.

2.7. Biodegradability

The biodegradability of the K/P edible films was assessed using a method adapted from Abdillah & Charles (2021). Square film samples (20 mm × 20 mm) were buried in composting soil in an outdoor environment. The degradation process was qualitatively evaluated by photographing the remaining samples with a smartphone camera every seven days.

2.8. Application of K/P edible film on tilapia fillets

The edible film was applied to tilapia fillets following the methodology of Nasution et al. (2024), with minor modifications. Fresh tilapia was filleted, cleaned to remove bones and skin, and cut into uniform cubes weighing of 10 ± 4 g for each sample. The fillet samples were placed in an 8 × 8 cm thin-walled container, and the top container was covered with an 11 × 11 cm edible film (Fig. 7). The wrapped samples were stored at a refrigerated temperature of 4 ± 2 °C for 6 days, and their weight loss was measured using an analytical balance (OHAUS PX224, Parsippany, New Jersey, USA with capacity 220 g at 3 and 6 days. The control group consisted of tilapia fillets wrapped with kappa-carrageenan-only edible films (without pedada flour) (KP0) and fillets stored without any film coating, to evaluate the relative effectiveness of K/P composite films.

2.9. Statistical analysis

The quantitative experiment was conducted based on randomized experimental design with at least triplicate (n=3) each group. All quantitative data were analyzed using a one-way analysis of variance (ANOVA) and were continued analyzed using Duncan's Multiple Range Test at a confidence level of 95% ($p < 0.05$). Statistical analyses were performed using IBM SPSS Statistics software, version 22.

Table 1
Physico-mechanical and barrier properties of K/P edible films.

Parameters	KP 0	KP 0.125	KP 0.25	KP 0.5	KP 0.75
Thickness (mm)	0.071 ±0.009[c]	0.087 ±0.006[c]	0.105 ±0.015[b]	0.130 ±0.015[a]	0.128 ±0.008[a]
Elongation at Break (%)	36.33 ±7.19[b]	54.03 ±7.76[a]	39.81 ±3.81[b]	40.06 ±0.12[b]	41.21 ±3.94[b]
Tensile Strength (MPa)	24.69 ±1.96[b]	29.92 ±1.97[a]	33.61 ±3.17[a]	20.86 ±1.14[c]	17.80 ±2.06[c]
Young's Modulus (MPa)	173.06 ±20.40[a]	186.20 ±14.04[a]	190.70 ±8.23[a]	131.16 ±9.50[b]	91.05 ±21.35[c]
WVP (g. mm/m[2]. kPa.h)	0.0065 ±0.0045[c]	0.0087 ±0.0061[c]	0.0113 ±0.0013[c]	0.1519 ±0.0122[a]	0.1377 ±0.0071[b]
Opacity	0.91 ±0.10[d]	3.17 ±0.30[c]	5.96 ±1.20[b]	8.01 ±1.20 [a]	8.714 ±1.28 [a]
*L**	89.12 ±0.10[a]	83.86 ±0.79[b]	81.41 ±0.79[b]	74.87 ±1.35[c]	71.86 ±3.28[d]
*a**	1.41 ±0.01[c]	2.22 ±0.10[bc]	3.14 ±0.38[b]	5.53 ±0.49 [a]	6.25 ±1.36 [a]
*b**	-3.10 ±0.17[d]	4.45 ±1.34[c]	7.45 ±1.33 [b]	15.99 ±1.74 [a]	18.74 ±3.61 [a]
*ΔE**	4.23 ±0.13[d]	12.95 ±1.50[c]	16.85 ±1.50[c]	27.69 ±2.22 [b]	32.06 ±5.08 [a]

[1] KP 0 (Control): Kappa-carrageenan with no pedada flour; KP 0.125: 2.875% kappa-carrageenan with 0.125% pedada flour; KP 0.25: 2.75% kappa-carrageenan with 0.25% pedada flour; KP 0.5: 2.5% kappa-carrageenan with 0.5% pedada flour; KP 0.75: 2.25% kappa-carrageenan with 0.75% pedada flour.
[2] Differences superscript letters indicate significant results at $p<0.05$.

3. Results and discussion

3.1. Physico-mechanical characterization of K/P edible films

3.1.1. Visual aspect and optical properties

The visual appearance of an edible film is important for consumer acceptance. In this study, we evaluated the effect of pedada flour on the optical properties of kappa-carrageenan films by assessing their visual appearance, color, and opacity. All K/P film samples exhibited homogeneous, bubble-free surfaces, were flexible when folded, and displayed a characteristic brown color with some transparency (Fig. 1). For instance, a letter and logo placed beneath the film remained clearly visible.

The addition of pedada flour to kappa-carrageenan-based films resulted in a significantly different ($p<0.05$) lightness (L^*) value compared to the KP 0 control film (89.12), while K/P films depicted L^* value from 71.86 to 83.86. The increment of pedada flour into kappa-carrageenan-based film resulted in a lower L^* value. However, the color parameter (a^*) showed a significant increase ($p < 0.05$) with higher pedada flour concentrations, from 1.41, 2.22, 3.13, 5.52, 6.24 (KP 0; KP 0.125; KP 0.25; KP 0.5; and KP 0.75 films, respectively). Similarly, the yellow-blue axis (b^*) values also showed a significant increase ($p < 0.05$), shifting from -3.10 to 18.73 with the addition of pedada flour to the formulations.

Accordingly, the K/P edible film showed a high total color difference (ΔE^*), ranging from 4.23 to 32.06. This indicates a significant deviation from the reference standard and is directly related to the films' color intensity and transparency (Table 1). As the concentration of pedada flour increased, the films became less transparent and more opaque. In this study, the opacity value increased from 3.17 to 8.71 (K/P Films), significantly higher than control (KP 0). This phenomenon had been attributed to the composition of pedada flour starch, which contained polysaccharides such as amylose. The highly branched structures of amylose and amylopectin scatter light, thereby reducing light transmission through the film (Karnwal et al., 2025). In contrast, kappa-carrageenan is composed of more linear sulfated galactose polymers, which allow light to pass through more easily, resulting in greater transparency (Ismawanti et al., 2020). Therefore, films with higher pedada flour and lower kappa-carrageenan content are more opaque due to the increased concentration of light-scattering glucose polymers.

A reduction in kappa-carrageenan and an increase in pedada flour led to a decrease in brightness and a more intense film color. The linear structure of kappa-carrageenan permits greater light penetration, producing brighter films. In contrast, the branched amylopectin in *pedada* starch scatters and restricts light, reducing brightness (Esfandiari et al., 2025). The higher starch content enhances coloration because starch absorbs light than carrageenan. Ultimately, a film's opacity to visible light is determined by the combined effects of its brightness, color, transparency, thickness, and absorbance (Zhang et al., 2020). In contrast, to the more transparent films formed by the linear galactose polymers in pure carrageenan (Esfandiari et al., 2025). This increased opacity is reinforced by stronger intermolecular bonding, where hydrogen bonds between amylose and amylopectin create a thicker matrix that hinders light transmission (Dong et al., 2025).

3.1.2. Film thickness

The thickness of the edible films ranged from 0.071 to 0.130 mm, with significant differences ($p < 0.05$) observed among the various K/F formulations (Table 1). The higher thickness of the K/P edible film was presented by KP 0.5 (0.130 mm) and KP 0.75 (0.128mm), followed by KP 0.25 (0.105 mm) and KP 0.125 (0.087mm), while the control film (KP 0) showed significantly lower thickness of 0.071 mm. This trend shows that higher concentrations of pedada flour in the film-forming solution resulted in higher thickness corresponding to increased solid content.

Film thickness is generally influenced by the number of dry materials used. In this case, formulations with lower kappa-carrageenan and higher pedada flour content produced thicker films, as the starch/flour contributes significantly to the total solids (Esfandiari et al., 2025). In this study, the thickness value of K/P edible films was reported in the range of edible film thickness (0.050–0.25 mm) that could be developed as food wrap packaging (Hamed et al., 2022), resulting from the distinct polymer structures of the two main components. Kappa-carrageenan is composed of linear, unbranched sulfated galactose polymers that tend to form a less-dense matrix (Jabeen et al., 2025). In contrast, the amylose and amylopectin in *pedada* flour have a highly branched structure that promotes the formation of a more solid film (Zhang et al., 2024a). Furthermore, the glycerol plasticizer contributes to this effect by forming bonds with the starch molecules. These interactions occupy space within the edible film matrix, pushing the starch polymers further apart, thereby increasing the overall thickness (Akachat et al., 2025).

3.1.3. Tensile strength and elongation at break (EAB)

The tensile strength of K/P films showed a significant difference ($p < 0.05$). The highest value was recorded for the KP 0.25 (33.61 MPa) and KP 0.125 (25.05 MPa), followed by KP 0 (24.69 MPa), and the lowest was exhibited by KP 0.5 (20.86 MPa) and KP 0.75 (17.80 MPa) (Table 1). For packaging applications, edible films must possess physico-mechanical properties comparable to conventional plastic-based polymers. Tensile strength measures the molecular bond strength that resists pulling forces before the film breaks; a higher value indicates a more robust and durable material (Mangala et al., 2025). Tensile strength testing revealed a maximum value of 33.61 MPa, indicating that an increment of 0.25 pedada flour concentration results in higher tensile strength, but after the addition of 0.5 and 0.75% of pedada, a lower tensile strength value was obtained. The decline in tensile strength with higher pedada flour content is likely due to changes in the polymer network. Additives such as plasticizers can promote hydrogen bonding within polymer chains, altering molecular mobility and disrupting the film's structural integrity (Chen et al., 2025). The glucose polymers in pedada flour are held together by hydrogen and glycosidic bonds that

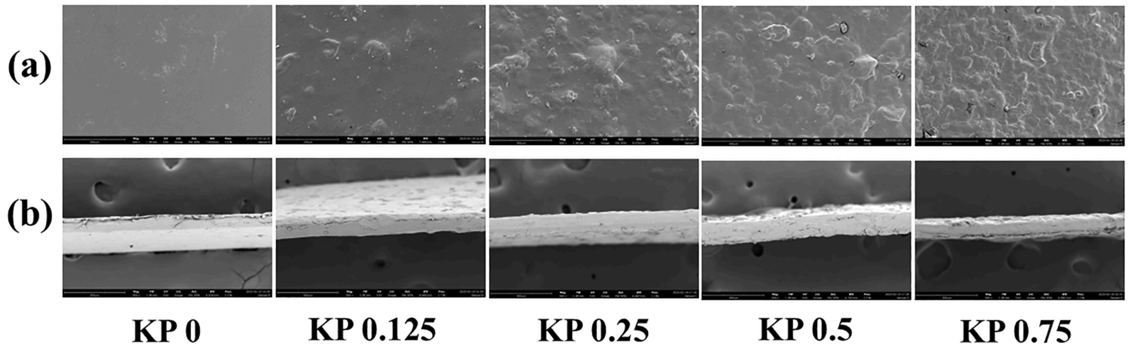

Fig. 2. Scanning electron microscope and laser microscope analyses of K/P edible films; (a) 500× surface section; (b) 500× cross section; KP 0 (Control): Kappa-carrageenan with no pedada flour; KP 0.125: 2.875% kappa-carrageenan with 0.125% pedada flour; KP 0.25: 2.75% kappa-carrageenan with 0.25% pedada flour; KP 0.5: 2.5% kappa-carrageenan with 0.5% pedada flour; KP 0.75: 2.25% kappa-carrageenan with 0.75% pedada flour.

are inherently weaker than the combined hydrogen and ionic bonds in KC (Zhang et al., 2024a). The weak bonding between pedada flour and low kappa-carrageenan concentrations leads to reduced intermolecular forces, consequently decreasing the tensile strength (Abdillah et al., 2024). However, all the K/P edible film formulations in this study fall within the recommended standard range of approximately 10–100 MPa reported by Hun & Gennadios, (2005). Furthermore, the Young's modulus of the K/P edible film showed a similar trend to the TS value. The highest and optimum value was observed with KP 0.25 (190.70 MPa), followed by KP 0 (173.06 MPa), KP 0.125 (186.2 MPa), KP 0.5 (131.16), and the lowest with KP 0.75 (91.05 MPa).

In contrast, the EAB values of the K/P films, ranging from 39.81% to 54.03% (Table 1), showed a significant difference ($p < 0.05$) from the control (KP 0) (36.33%). The EAB determines a film's flexibility and ability to stretch without breaking, which is essential for handling and application (Pawle et al., 2025). In this study, the higher addition of pedada flour (0.75%) tended to result in a lower EAB value. This reduction occurs because the molecular bonds in starch are weaker than the ionic bonds in kappa-carrageenan (Jabeen et al., 2025). Accordingly, the optimum combination of kappa-carrageenan with pedada flour (0.125% and 0.25%) resulted in higher flexibility and a good tensile strength which could be suggested for food wrap application. The addition of glycerol as a plasticizer helps mitigate brittleness and improve flexibility to enhance the elongation properties of the films (Sartika et al., 2022). In theory, (de Souza et al., 2022) suggested that the thickness of the films increased with higher cassava starch concentrations, which also correlated with increased tensile strength but decreased elongation at break. Accordingly, the incorporation of pedada flour into kappa-carrageenan-based edible film increased thickness and increased the tensile strength, but a higher amount of incorporation of pedada flour (0.5 and 0.75%) resulted in a decrease in tensile strength value. Flour, particularly wheat flour, is another biopolymer used in edible film production. Wheat flour-based films have shown good mechanical properties and thermal stability. The incorporation of gluten can improve the density and processability of the film-forming solution, although it may reduce surface smoothness and water vapor barrier performance (Wang et al., 2022). In addition, higher protein content in flour can enhance the Maillard reaction, which can significantly alter the mechanical and barrier properties of films. For example, films modified through the Maillard reaction exhibited improved tensile strength, water resistance, and reduced solubility (Capuano et al., 2010; Jitphongsaikul et al., 2025; Kchaou et al., 2018; Qie et al., 2020).

3.1.4. Scanning electron microscope (SEM) and laser microscope analysis

SEM images of the K/P edible films' surface and cross-section are shown in Fig. 2. Micrographs showed that as the pedada flour concentration increased, the film surface became more textured compared to the smooth KP 0 (control). The cross-sectional structure also became more textured and compact with higher pedada flour content. This texture had been caused by pedada flour rich in polysaccharides forming an amorphous matrix with high crystallinity and kappa carrageenan forming strong sulfated gels through double helix bonds. Phase inhomogeneity had resulted in microscopic aggregation and superficial cracks during the edible film drying process (Esfandiari et al., 2025).

The incorporation of pedada flour into the kappa-carrageenan matrix resulted in a relatively dense structure, suggesting good compatibility between the two components. However, at the highest flour concentration (KP 0.75), the film surface became rough and the cross-section exhibited a wavy morphology, coinciding with a decline in tensile strength. This structural deterioration can be attributed to the reduced concentration of kappa-carrageenan, which diminished the effective hydrogen bonding between its hydroxyl (-OH) and carboxyl (-COOH) groups and those of the starch. With fewer of these strong interactions, the overall mechanical integrity of the film was compromised (Prasetyaningrum et al., 2024).

3.2. Water vapor permeability of K/P edible films

The WVP of K/P edible films are described in Table 1. Increment of pedada flour into kappa-carrageenan-based edible films presented a significant difference ($p < 0.05$) of WVP. The highest WVP value was recorded for the KP 0.5 film (0.1519 g.mm/m^2. kPa.h), while the control film (KP 0) exhibited the lowest (0.0065 g.mm/m^2. kPa.h). This can occur because the addition of external components to the carrageenan matrix tends to increase WVP due to the formation of a more open and less compact film structure (Cheng et al., 2022). WVP is a crucial parameter that determines an edible film's effectiveness as a barrier to moisture transfer, which is essential for preserving food quality. In the initial stage, the increase in WVP occurs because the addition pedada flour disrupts the regularity of the pure carrageenan polymer network, thereby creating a free volume that allows water molecules to diffuse more easily. WVP values are influenced by the chemical properties and structure of the polymers, as well as the testing conditions (Jain et al., 2025).

Moreover, the WVP values observed in this study (KP 0, KP0.125, and KP 0.25) are consistent with those reported for other polysaccharide-based films, such as pectin films measured via ASTM E96 methods, which range from 0.008 to 0.011 g/m^2·24h (Saidi et al., 2025). This discrepancy can be primarily attributed to differences in the concentration of the film-forming agents and the specific testing conditions used, such as relative humidity and temperature gradients, which significantly influence water molecule kinetic energy (Saidi et al., 2025). Differences in the concentration of the film-forming agent and the specific testing conditions used, such as relative humidity and temperature gradient, had significantly affected the kinetic energy of water molecules (Esfandiari et al., 2025). Additionally, the combination

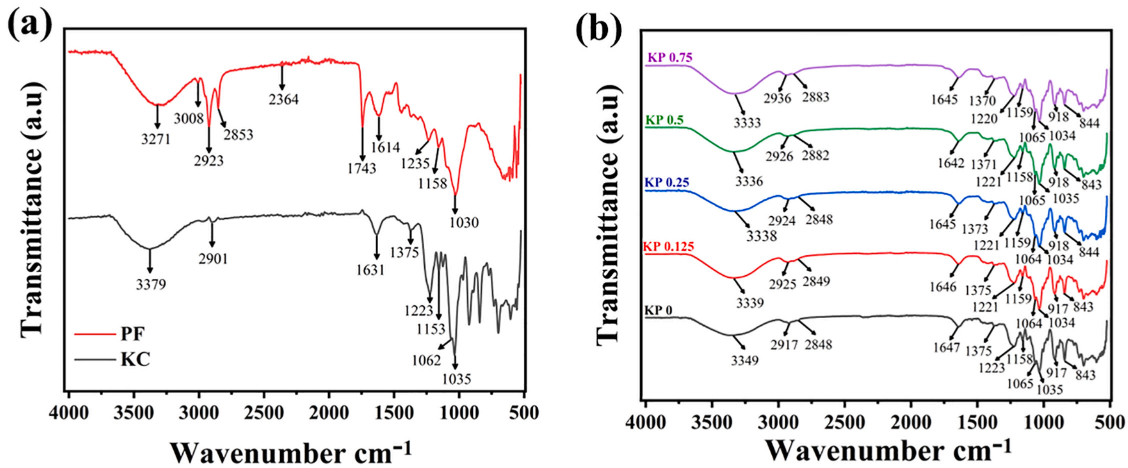

Fig. 3. Fourier transform infrared analysis (FTIR); (a) pedada flour (PF) and Kappa-carrageenan (KC) separately; (b) K/P edible films; KP 0 (Control): Kappa-carrageenan with no pedada flour; KP 0.125: 2.875% kappa-carrageenan with 0.125% pedada flour; KP 0.25: 2.75% kappa-carrageenan with 0.25% pedada flour; KP 0.5: 2.5% kappa-carrageenan with 0.5% pedada flour; KP 0.75: 2.25% kappa-carrageenan with 0.75% pedada flour.

of kappa-carrageenan and cassava flour had likely formed a more convoluted and dense network through synergistic hydrogen bonding, thereby increasing resistance to moisture permeation (Pérez-Vergara et al., 2020).

3.3. Fourier transform infrared analysis (FTIR)

The FTIR spectra of kappa-carrageenan, pedada flour, and composite K/P films show the molecular interactions that form the blended system (Fig. 3). The KC spectrum displays its typical features, including O–H stretching near 3379 cm^{-1}, C–H stretching at 2901 cm^{-1}, sulfate ester bands at 1223 and 1153 cm^{-1}, and anhydro-galactose markers at 918 and 843 cm^{-1}. These peaks confirm the presence of S=O stretching and the C–O–SO_3 group at the C-4 position of galactose, which are standard fingerprints for kappa carrageenan (Kalita et al., 2025). The pedada flour spectrum shows characteristic polysaccharide bands a broad O–H stretch around 3270 cm^{-1}, aliphatic C–H vibrations at 2923 and 2853 cm^{-1}, and strong C–O–C stretching between 1158 and 1030 cm^{-1}. These signatures align with previous studies confirming the sulfate-rich structure of kappa-carrageenan and the polysaccharide composition of pedada flour (Golea et al., 2023).

In the composite films, the spectra show signals from both pedada flour and kappa-carrageenan, but with notable shifts. The hydroxyl region (3330–3349 cm^{-1}) broadens and shifts, indicating enhanced hydrogen bonding between the hydroxyl groups of pedada flour and the hydroxyl or sulfate groups of kappa-carrageenan. This kind of band broadening is a known effect in biopolymer blends like starch-carrageenan and chitosan-carrageenan systems due to hydrogen bonds forming the composite network (Qureshi et al., 2024; Yang et al., 2025). Variations in intensity and position within the sulfate ester region (1220–1159 cm^{-1}) indicate electrostatic interactions between negatively charged sulfate groups in kappa-carrageenan and hydroxyl or protein residues in pedada flour, consistent with observations of sulfate–amide interactions influencing protein–carrageenan network structures (Kim et al., 2025). Increased absorption between 1640 and 1650 cm^{-1} reflects bound water involvement and protein-sulfate interactions, resembling structured water networks in *S. caseolaris*–agar and starch–xanthan polysaccharide hydrogels (Li et al., 2025; Lu et al., 2023). The absence of new absorption bands confirms that these associations are physical, dominated by hydrogen bonding and ionic interactions within the K/P matrix (Cheng et al., 2024).

Varying the K/P ratio modulates the strength of molecular interactions within the film. pedada flour-rich mixtures show enhanced carbonyl and amide absorption bands, whereas kappa-carrageenan rich

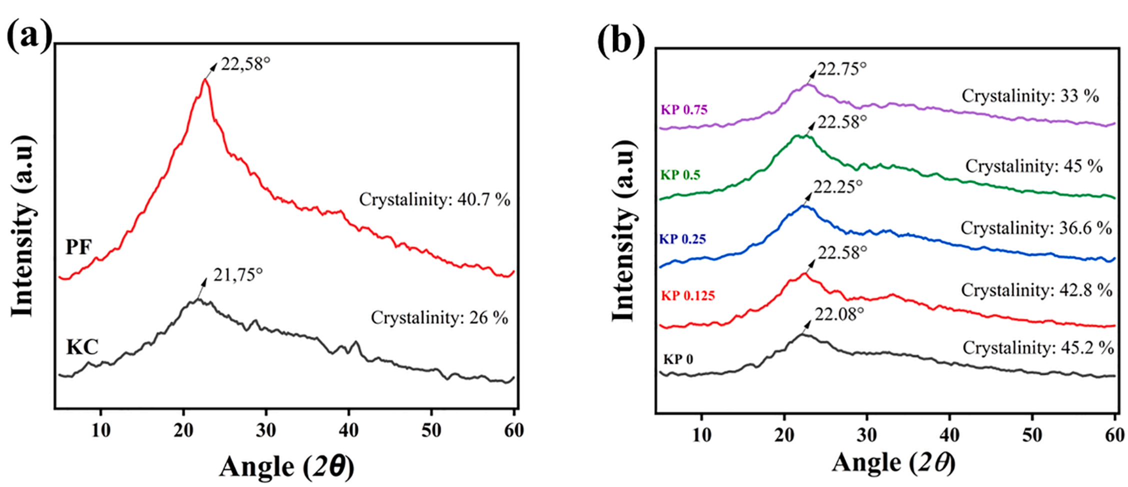

Fig. 4. X-Ray diffraction analysis; (a) pedada flour (PF) and Kappa-carrageenan (KC) separately; (b) K/P edible film; KP 0 (Control): Kappa-carrageenan with no pedada flour; KP 0.125: 2.875% kappa-carrageenan with 0.125% pedada flour; KP 0.25: 2.75% kappa-carrageenan with 0.25% pedada flour; KP 0.5: 2.5% kappa-carrageenan with 0.5% pedada flour; KP 0.75: 2.25% kappa-carrageenan with 0.75% pedada flour.

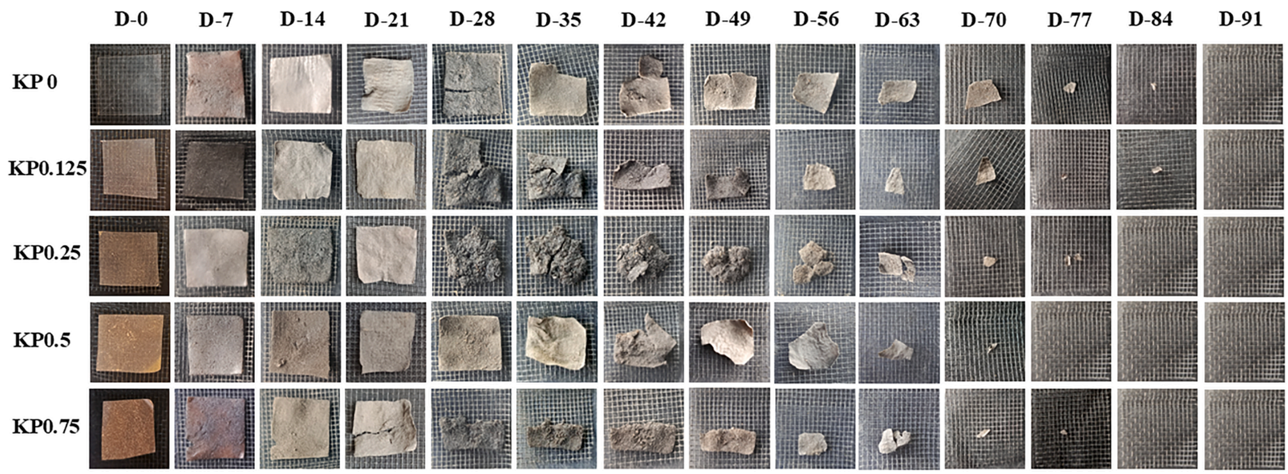

Fig. 5. Biodegradability of K/P edible films; KP 0 (Control): Kappa-carrageenan with no pedada flour; KP 0.125: 2.875% kappa-carrageenan with 0.125% pedada flour; KP 0.25: 2.75% kappa-carrageenan with 0.25% pedada flour; KP 0.5: 2.5% kappa-carrageenan with 0.5% pedada flour; KP 0.75: 2.25% kappa-carrageenan with 0.75% pedada flour.

systems produce stronger sulfate ester signals. This compositional dependence mirrors findings in arrowroot starch/kappa-carrageenan films (Abdillah et al., 2024), indicating that interactions between hydroxyl and sulfate groups influence physicochemical properties. In both systems, an optimal ratio facilitates more effective molecular associations, whereas an imbalance leads to less favorable structural organization. The FTIR results confirm that pedada flour and kappa-carrageenan form physically crosslinked networks through hydrogen bonding and electrostatic interactions, which is characteristic of polysaccharide-hydrocolloid blends. These tunable, non-covalent associations are likely responsible for modulating the composite's gelation, viscosity, and water retention, underscoring the potential of K/P blends for food, pharmaceutical, and biodegradable packaging applications. Accordingly, arrowroot starch could act as a sustainable local source of hydrocolloids for building functional biopolymer networks (Abdillah et al., 2024).

3.4. X-ray diffraction (XRD) analysis

Fig. 4 shows the X-ray diffraction (XRD) patterns for pedada flour, kappa-carrageenan, and their composite films. pedada flour displays a characteristic diffraction peak at 22.6° with a relative crystallinity of 40.7%, confirming its semi-crystalline nature. This level of crystallinity is typical for polysaccharides like amylose and amylopectin, where hydrogen bonding between starch chains and residual granule structures creates areas of partial order, consistent with previous studies of pedada flour (Sun et al., 2023). In contrast, kappa-carrageenan shows a broad amorphous halo centered at 21.8° and a lower crystallinity of 26% (Croitoru et al., 2020). This lack of structural order results from the irregular sulfate ester groups along its polymer chain, which disrupt molecular packing and prevent the formation of large crystalline domains. This is a common feature of sulfated polysaccharides like carrageenan, agar, and alginate (Muthukumar et al., 2021).

The K/P composite films exhibit features of both components, with broadened peaks in the 21–23° range. Their relative crystallinity varies with composition, ranging from 33% to 45%. Notably, balanced ratios, such as KP 0.5, yield higher crystallinity than either pure component. This suggests that intermolecular interactions, likely hydrogen bonding between the hydroxyl groups of pedada flour and the sulfate groups of kappa-carrageenan, promote a more ordered alignment of the polymer chains. A similar enhancement of ordered domains through molecular compatibility has been observed in other composites like starch-chitosan and protein-carrageenan (Alimi et al., 2023; Berton et al., 2020). Conversely, imbalanced mixtures, such as KP 0.75, show reduced crystallinity. The high pedada flour content in these films appears to cause steric hindrance and structural incompatibility, disrupting molecular packing. This composition-dependent behavior shows a dual functionality in polysaccharide blending, where moderate compatibility can enhance structural order, while a significant imbalance can disrupt it. Such non-linear effects of mixture ratios on crystallinity have also been reported in other systems, like gelatin-polysaccharide blends (Qiao et al., 2023).

Variations in component ratios influence crystallinity levels, but peak positions near 22° remain consistent across mixtures, indicating that compositional adjustments modify structural order without generating new crystalline phases. The absence of any additional diffraction peaks confirms that no chemical modifications occurred during mixing, with interactions between pedada flour and kappa-carrageenan being purely physical in nature. XRD findings, supported by FTIR results, demonstrate that hydrogen bonding and electrostatic interactions between pedada flour and kappa-carrageenan facilitate molecular association and affect structural organization.

The broad amorphous halo identified in XRD analysis of kappa-carrageenan at 21.8° (26% crystallinity) aligned directly with the microscopic aggregation and surface cracks observed through SEM during the drying process, thus verifying that irregular sulfate esters had obstructed molecular packing and induced phase separation (Russo Spena & Grizzuti, 2025). Pedada flour incorporation had conversely fostered enhanced compactness through physical hydrogen bonding between starch -OH/-COOH groups and kappa-carrageenan, although excessive pedada flour levels weakened these interactions and eroded mechanical integrity (Prasetyaningrum et al., 2024). These crystallinity-texture relationships had accounted for the tunable stiffness seen at higher crystallinity versus greater flexibility and swelling capacity in amorphous regions of K/P films, rendering such composites well-suited for controlled-release food packaging and biodegradable coatings (Charles et al., 2025).

3.5. Biodegradability test

The biodegradability assessment revealed that the K/P edible films degraded significantly and continuously in a natural soil environment (Fig. 5). Observations over 91 days, recorded at seven-day intervals for five different formulations, showed a clear link between the film's composition and its degradation rate. The rapid degradation of the films can be largely attributed to the unique biochemical profile of pedada flour. Pedada flour has a high crude fiber content and complex carbohydrates, making it an organic material that is easily degraded by

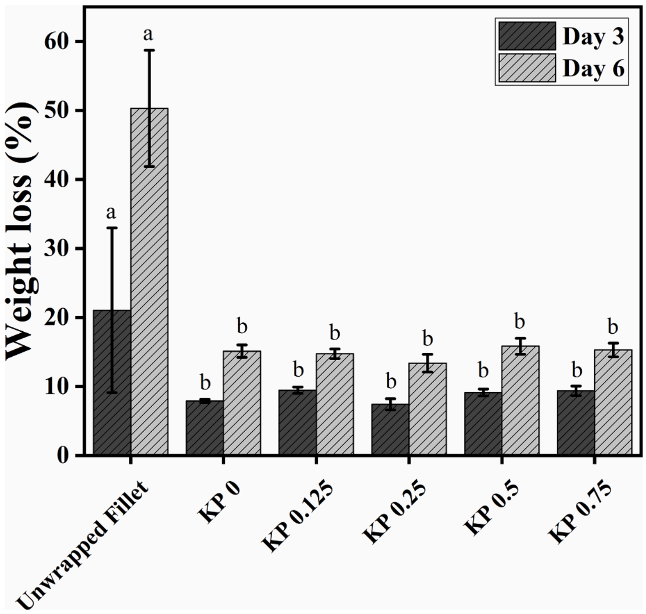

Fig. 6. Weight loss of tilapia fillets; comparison between samples unwrapped and wrapped with K/P edible film mixtures; KP 0 (Control): Kappa-carrageenan with no pedada flour; KP 0.125: 2.875% kappa-carrageenan with 0.125% pedada flour; KP 0.25: 2.75% kappa-carrageenan with 0.25% pedada flour; KP 0.5: 2.5% kappa-carrageenan with 0.5% pedada flour; KP 0.75: 2.25% kappa-carrageenan with 0.75% pedada flour. Differences superscript letters indicate significant results at $p<0.05$.

microbes (Dari et al., 2022). Furthermore, the inclusion of pedada flour increases the film's hydrophilicity, encouraging moisture absorption from the soil which facilitates microbial colonization and accelerates the loss of structural integrity (Kalita et al., 2025). Films with a higher pedada flour content and a correspondingly lower kappa-carrageenan content broke down faster than those richer in kappa-carrageenan.

The degradation period of the edible films is influenced by polymer breakdown, affected by factors such as ionic bond strength, oxygen concentration, temperature, availability of inorganic nutrients, and moisture content, all of which affect microbial activity (Maran et al., 2014). Kappa-carrageenan contains strong ionic bonds that enhance matrix cohesion in the edible film, making it more resistant to degradation (Zhang et al., 2024b). Additionally, the use of soil as a testing medium can prolong the observed degradation time, as the process involves the gradual fragmentation of large polymer molecules into smaller and more readily assimilated components (Choudhary et al., 2023).

3.6. Application of K/P edible film on tilapia fillets

Weight loss measurements on Nile tilapia fillets demonstrated significant differences between the uncovered control and treatments with edible films (Fig. 6). The uncovered control sample exhibited the highest weight loss, reaching 21.03% on day 3 and rising to 50.29% by day 6. In contrast, fillets wrapped with the KP 0.25 edible film exhibited the best preservation, with weight losses of only 7.41% on day 3 and 13.36% on day 6. Increasing pedada flour concentration while decreasing kappa-carrageenan significantly reduced weight loss, indicating the edible film's effectiveness in preserving the freshness of tilapia fillets. The lower weight loss in fillets coated with K/P edible films suggest its ability to inhibit shrinkage by reabsorbing water from fish muscle. This decrease correlates with the edible film's low water vapor permeability, which effectively limits sample respiration rates (Gumus et al., 2024). These findings align with studies who noted that edible coatings reduce water loss, moderate respiration, and extend shelf life (Raj et al., 2024). By acting as a physical barrier, the edible film prevents excessive shrinkage of tilapia fillets compared to the control, which experiences more rapid weight loss during storage due to unchecked respiration processes where high oxygen consumption breaks down complex cellular compounds, accelerating deterioration (Nouri et al., 2025). Application of K/P edible film on Tilapia fillets were presented in Fig. 7.

4. Conclusions

Pedada flour was successfully incorporated into kappa-carrageenan matrices to produce biodegradable edible films with altered physicomechanical, barrier, and degradation characteristics. Film formation occurred through non-covalent interactions, resulting in increased thickness and biodegradability with increasing pedada flour content. The addition of 0.125 and 0.25% of pedada flour into kappa-carrageenan-based edible films showed the optimum mechanical properties (good tensile properties and young's modulus) compare with kappa-carrageenan film (control). In addition, the K/P edible films exhibited reduction of weight loss of tilapia fillets compare with unwrapped samples during storage at 4°C. Further studies will be conducted by incorporate halochromic natural dyes and or active compound such as antimicrobial or antioxidant to develop smart active films that could show the freshness and extend the self-life food product during storage.

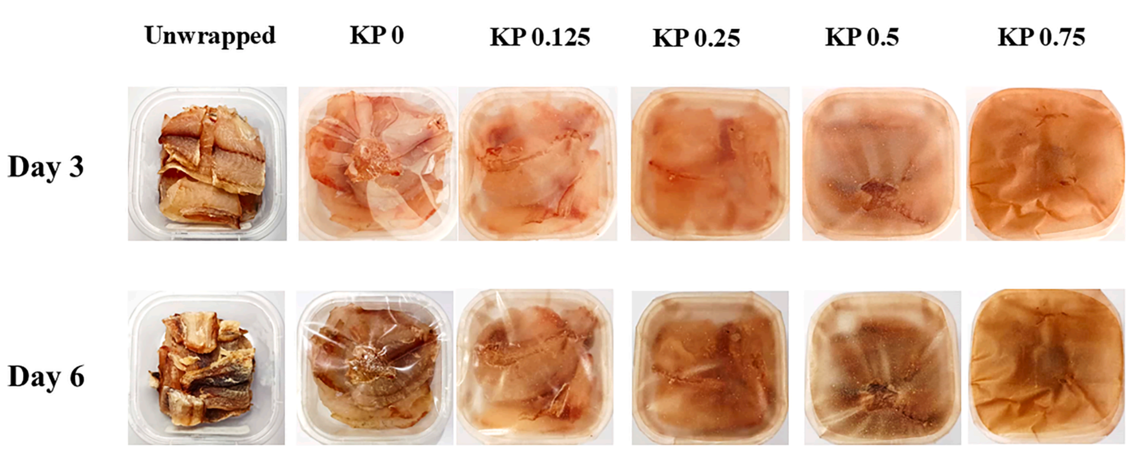

Fig. 7. Application of freshness to tilapia fillets unwrapped and wrapped with K/P edible film mixtures; KP 0 (Control): Kappa-carrageenan with no pedada flour; KP 0.125: 2.875% kappa-carrageenan with 0.125% pedada flour; KP 0.25: 2.75% kappa-carrageenan with 0.25% pedada flour; KP 0.5: 2.5% kappa-carrageenan with 0.5% pedada flour; KP 0.75: 2.25% kappa-carrageenan with 0.75% pedada flour.

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Ethical statement

This study did not engage animal and humans

CRediT authorship contribution statement

Annur Ahadi Abdillah: Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization. **Puspitasari Habi Putri:** Writing – original draft, Investigation, Data curation, Conceptualization. **Nia Nandasari:** Investigation, Formal analysis, Data curation. **Ajeng Pramudita Anggraeni:** Investigation, Data curation. **Eka Saputra:** Investigation, Data curation. **Dwi Yuli Pujiastuti:** Investigation, Data curation. **Ahmad Shofy Mubarak:** Investigation, Data curation. **Mochammad Amin Alamsjah:** Methodology, Conceptualization.

Declaration of competing interest

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

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.afres.2026.101954.

Data availability

Data will be made available on request.

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