

The Effect of Heat Treatment Duration on the Psychochemical, Mechanical, and Biodegradability of Polyvinyl Alcohol/Gambir Extract Biocomposite Films

Ainul Kahfi Muhlasin¹, Poppy Puspitasari^{1,2*}, Heru Suryanto^{1,3}, Diki Dwi Pramono^{1,2}, Dieter Rahmadiawan⁴, Billie Jack Pasion⁵

¹Department of Mechanical and Industrial Engineering, Universitas Negeri Malang, Indonesia

²Nanomaterials Engineering Research Center, Universitas Negeri Malang, Indonesia

³Center Excellent for Cellulose Composite (CECCom), Department of Mechanical and Industrial Engineering, Universitas Negeri Malang, Malang, East Java, Indonesia

⁴Department of Mechanical Engineering, Universitas Negeri Padang, Padang, 25173, West Sumatra, Indonesia

⁵College of Industrial Technology, Nueva Ecija University of Science and Technology, Philippines

*Corresponding author: poppy@um.ac.id

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ABSTRACT

This study investigates PVA-based films with the addition of gambir and heat treatment to improve the characteristics of the film. Methods include the synthesis of PVA film with gambir addition (0.5%), treated by heat treatment for 40 minutes and 60 minutes. The film was characterised by physicochemical, mechanical properties, and biodegradability. Data was analyzed using ANOVA with a significance of 95%. Results indicate that the surface of PVA/gambir films is smoother and more homogeneous as the heat treatment duration increases. New peaks of functional groups were identified after the addition of gambir at the C-C and C-O groups. After heat treatment for 40 minutes, the film increases in crystallinity index, hydrophilicity, and the PVA/Gambir provides UV-A protection. Gambir addition does not significantly change hydrophilicity, whereas heat-treatment duration does. The biodegradation of PVA/Gambir (0.5%)-H40 film shows the highest biodegradation value of 18.66% on the 16th day. Gambir addition, heat-treatment duration and time period each significantly affect biodegradability. The PVA/Gambir film with 40 minutes of heat treatment had the highest tensile strength of 47.82 N/mm² and elongation of 25.24%. However, the addition of gambir and heat treatment did not significantly affect tensile strength. The addition of gambir did not significantly affect elongation, but heat treatment had a significant effect.

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Keywords: Biocomposite, gambir, heat treatment, polyvinyl alcohol.

I. Introduction

Plastic packaging made from petroleum-based polymers has attracted considerable interest. However, the use of these materials in large quantities has caused serious environmental problems [1]. This issue has sparked considerable interest among researchers in developing biodegradable polymers. One biodegradable polymer that has attracted significant attention is polyvinyl alcohol (PVA). PVA is a semi-crystalline synthetic polymer having properties of biodegradable, non-toxic, and water-soluble [2]. PVA is widely used in various applications such as textiles, adhesives, and food packaging [4]. PVA is completely degraded into CO₂ and H₂O in wastewater and soil through microorganisms [5]. However, despite the excellent characteristics of PVA, it has poor ultraviolet (UV)



protection, high water absorption, thermal properties, and mechanical properties [6]–[8]. Therefore, to reduce these weaknesses and improve the characteristics, PVA films can be improved by adding fillers such as [9], chitosan [10], cellulose [11], and extracts from plants containing phenolic compounds, one of which is gambir [12].

Indonesia is one of the biggest gambir producers in the world, with 19,825 tons and a total plantation area of 32,000 hectares in 2023 (Directorate General of Plantations, Indonesia, 2023). Gambir extract contains a main compound called catechin (a type of phenolic compound), which acts as an antioxidant and antimicrobial [13],[14]. The substances contained in gambir extract can facilitate chemical bonds in the PVA framework, resulting in better intermolecular relationships and a more orderly structure [15]. Guan *et al.* [16] show that the addition of natural polyphenol compounds to PVA-based films can improve crystallinity, mechanical properties, and thermal properties through hydrogen bonding. Zhang *et al.* [17] found that adding polyphenol compounds derived from tea to PVA/Pullulan/Nano-cellulose-based films can improve thermal properties, hydrophobic properties, and UV absorption. Rahmadiawan *et al.* [18] was found that PVA with the addition of gambir (1%) and zinc oxide can improve UV properties, antibacterial properties, hydrophobicity, and mechanical properties. The combined effect of PVA and gambir shows promising potential and supports environmentally friendly and sustainable materials.

The use of a combination of PVA and gambir using other methods to maximize their existing advantages has not been widely researched. One method that can be used is heat treatment. Heat treatment is one method for causing physical crosslinking between PVA molecules through hydrogen bonds [3]. Heat treatment triggers physical crosslinking by removing water, thereby reducing the distance between PVA chains and making the hydrogen bond network between hydroxyl groups tighter and more regular [19]. Sau *et al.* [3] found that a 40-minute heat treatment could improve the structural, mechanical, and optical properties. This improvement may be due to crosslinking between molecules and between intermolecularly in PVA as a result of heat treatment. Abrial *et al.* [12] showed that the addition of gambir (0.05%, 0.5%, and 1%) to PVA can improve UV and antibacterial properties as well as mechanical properties. However, this study has not discussed heat treatment methods and focuses more on gambir concentration. In a study conducted by Rahmadiawan *et al.* [20], PVA/gambir film treated with heat for 40 minutes can improve hydrophilicity, tribology properties, and hardness. Higher heat treatment durations have not yet been extensively studied. Excessive increases in heat treatment duration can cause film degradation, resulting in a decrease in film characteristics. Therefore, optimizing the duration of heat treatment is very important in improving film characteristics.

However, studies on the addition of gambir and its combination with heat treatment duration on PVA-based films to improve characteristics have not been widely discussed and studied. Therefore, this study comprehensively examines the effect of adding gambir extract and heat treatment in improving film characteristics. This study aims to characterize the physicochemical, mechanical, and biodegradability of PVA-based films with the addition of gambir extract (0.5%) and heat treatment duration (40 and 60 minutes).

II. Material and Methods

1. Materials

The gambir extract powder used in this study contained approximately 90% catechins. The gambir extract powder was obtained from PT. Andalas Sitawa Fitolab, Indonesia.

Distilled water (Onelab, Indonesia). The analytical grade PVA (99% hydrolysed) was acquired from Sigma-Aldrich, Germany.

2. Preparation of PVA/Gambir Film

Dry gambir powder (0.5 wt.%) was combined with 100 mL of distilled water, then stirred using a magnetic stirrer (Thermo Fisher Sci., USA) at 50°C and 500 rpm for 30 minutes in a 250 mL measuring cup (Pyrex, Indonesia). The stirred suspension is then centrifuged (Oregon LC-04R, China) for 30 min at 500 rpm. The centrifuged suspension was separated from the residue using filter paper. PVA powder was added to the gambir solution at a 1:10 ratio, and the mixture was heated to 80°C and stirred at 500 rpm for 2 hours until gelatinization was achieved. For the next step, the PVA/gambir gel produced was sonicated (LUH-103, UK) at 600 W for 5 minutes. The sonicated PVA/gambir gel was placed in a petri dish. The PVA/gambir film was dried in an oven (Memmert UN110, Germany) at 50°C for 22 hours. After the film was completely dry, the untreated PVA/gambir film samples were stored in a desiccator (WH). The PVA/gambir film samples to be heat-treated were further heated at 100°C for 40 and 60 minutes. The samples to be characterized were labelled as follows: pure PVA film samples, namely PVA-WH (untreated), PVA-H40 (40 min heat treatment), and PVA-H60 (60 min heat treatment). In contrast, films with gambir addition were PVA/gambir (0.5%)-WH (untreated), PVA/gambir (0.5%)-H40 (40 min heat treatment), and PVA/gambir (0.5%)-H60 (60 min heat treatment). A schematic diagram of the PVA/gambir film preparation process is shown in Figure 1, and the experimental design for this investigation is provided in Table 1.

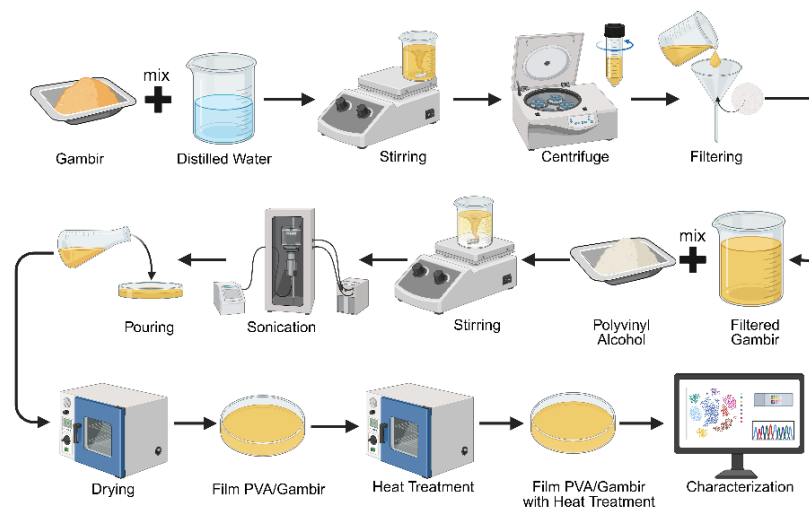


Fig. 1. Schematic of PVA/gambir film preparation

Table 1. Research design

No	Sample names	Gambir content (wt%)	Heat treatment duration (minutes)
1.	PVA-WH	0	0
2.	PVA-H40	0	40
3.	PVA-H60	0	60
4.	PVA/gambir (0.5%)-WH	0.5	0
5.	PVA/gambir (0.5%)-H40	0.5	40
6.	PVA/gambir (0.5%)-H60	0.5	60

3. Identification of Surface Morphology

Identification of surface morphology on film samples was performed using Scanning Electron Microscope (SEM) (FEI, Japan) with 1,000x magnification.

4. Identification of Functional Groups

Identification of functional groups in film samples was recorded using an FTIR model Prestige 21 (Shimadzu Instrument, Japan) at a wavelength of 500-4000 cm^{-1} .

5. Identification of Crystallinity Index

Identification of the crystallinity index in film samples was performed using X-ray diffraction (XRD). XRD testing was performed using PANalytical X'Pert Pro (Malvern Panalytical, UK) ($\lambda = 1.54$) at a diffraction angle of $2\theta = 10^\circ$ to 90° . The crystallinity index (CI) of the film sample is to be calculated using Eq. (1) [21] :

$$CI (\%) = \frac{(I_f - I_s)}{I_f} \times 100 \dots\dots\dots (1)$$

Where: I_f is the intensity peak of the base band at $2\theta = 18.5^\circ - 20^\circ$ and I_s is the intensity peak of the secondary band at $2\theta = 28.0^\circ - 28.5^\circ$.

6. Identification of Hydrophilicity

Identification of hydrophilicity using water contact angle measurements on film samples was performed according to the ASTM D7334 method, with assistance from ImageJ software. Water was dripped onto the film surface using a micropipette (TOPSCIEN, China) with a drop volume of 10 μL . Water was dropped onto the film surface and photographed as it touched the film surface. The contact angle measurement on the sample was repeated three times at different points. Statistical analysis of water contact angle was performed using two-way ANOVA with a significance level of 95%.

7. Identification of UV Protection

Identification of UV protection in film samples was performed using a UV-Vis spectrophotometer (Analytic Jena Specord 200 Plus, Germany) in the range of 200-1100 nm. Samples were prepared in sizes of 50 mm x 50 mm.

8. Identification of biodegradable

The biodegradability of the film was observed for 16 days using a soil burial test with 4-day intervals. The soil used has a pH of 6-8 and a soil moisture content of 60-90%, measured using an intelligent soil detector (Juanjuan, China). Samples were prepared in 1.5 cm pieces and weighed before and after testing. The test was repeated three times for each sample. The weight loss was determined using Eq. (2):

$$\text{Weight Loss (\%)} = \frac{W_0 - W_1}{W_0} \times 100 \dots\dots\dots (2)$$

It can be seen that W_0 is the initial weight before testing, and W_1 is the final weight after testing. Statistical analysis of biodegradability was performed using two-way ANOVA. P-values less than 0.05 were considered statistically significant.

9. Identification of Tensile Properties

The tensile properties of the film were determined in accordance with the ASTM-D638 standard using a tensile tester (JTM-UTC 10, Taiwan), with a triplicate sample. Data was analysed using two-way ANOVA with a significance level of 95%.

III. Results and Discussions

1. Identification of Surface Morphology

Figure 2 shows the surface morphology of pure PVA film samples and PVA/gambir films with different heat treatment durations. The PVA-WH film sample shows a rough, uneven surface morphology and contains particles that are not evenly mixed (Figure 2a). This may be caused by relatively weak intermolecular forces between the PVA chains [22]. In addition, the PVA/gambir-WH film samples also had a rough, uneven surface morphology and contained particles that were not evenly mixed due to changes in microstructure characteristics. The addition of gambir extract affects the roughness of the film surface due to the interaction between PVA molecules and gambir extract. Ismayati *et al.* [23] found that tannin compounds added to the PVA matrix made the film surface rougher. Film samples that were heat-treated for 40 minutes (Figures 2.b and e) showed a smooth surface morphology, but there were still particles that were not evenly mixed. This can be attributed to the fact that water evaporation during the heat treatment process can result in an uneven surface [24], [25]. Increasing the heat treatment duration (60 minutes) on the film resulted in a smooth and even surface morphology (Figures 2.c and f). This change is attributed to the heat treatment, which optimized the crosslinking process between PVA chains and between PVA and gambir. A higher level of crosslinking of molecular chains due to heat treatment can form a denser network structure [26]. The optimal duration of heat treatment can support the completion of the crosslinking reaction [27].

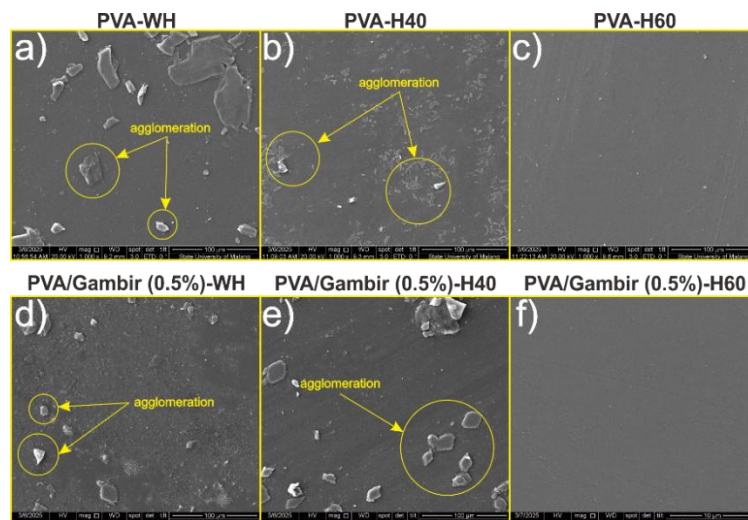


Fig. 2. Surface morphology of PVA/gambir film samples

2. Identification of Functional Groups

Figure 3 shows the FTIR graphs of the pure PVA film sample and the PVA/gambir film with different heat treatment durations. Based on the FTIR graph, there is an initial peak at around $3000\text{--}3750\text{ cm}^{-1}$ indicating O-H stretching vibrations [28], [29]. The second peak at around 2957.26 cm^{-1} indicates C-H stretching vibrations [3]. In the PVA-H40 and PVA/gambir (0.5%)-H40 samples, there is a peak at 2353.84 cm^{-1} , which can be attributed to carbon dioxide (CO_2) and does not originate from the chemical structure of PVA [30]. This result may be because heat treatment can increase the crystallinity of PVA and form microvoids/fine cracks due to the shrinkage of bound water, causing the physical absorption of CO_2 from the air on the surface/pores of the film. The addition of gambir extract produced new peaks at 1665.81 cm^{-1} and 1368.37 cm^{-1} , which represent C-C and C-O bonds

originating from catechin and other polyphenol-based compounds [27]. This finding agrees with the research by Abrial *et al.* [14], which found that adding 1% gambir to PVA-based films produced a new peak at approximately 1618 cm^{-1} , associated with catechin compounds. Meanwhile, the peak at 1151.50 cm^{-1} can be associated with C-O stretching in PVA [7]. The last peak at 862.39 cm^{-1} corresponds to the C-C vibration peak in the main chain of PVA [32], [33]. Heat treatment with different durations applied to all samples did not produce new peaks. This is because heat treatment only supports the physical rearrangement of polymer chains (hydrogen bonds) without forming new covalent bonds. Sau *et al.* [3] also found that heat treatment for 40 minutes aligns interchain PVA molecules through the formation of hydrogen bonds, which are generated by physical cross-links.

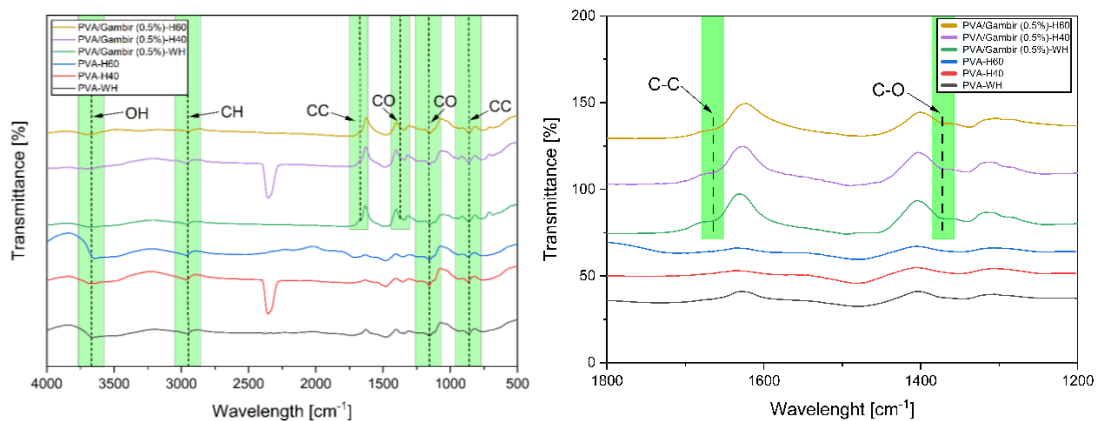


Fig. 3. FTIR graph of PVA/gambir film samples

3. Identification of Crystallinity Index

Figure 4 shows the XRD graphs of the pure PVA film sample and the PVA/gambir film with different heat treatment durations. Based on these patterns, it is known that all film samples show the same diffraction pattern with strong peaks observed at around $2\theta = 19.6^\circ$ and two weak peaks in the range of $2\theta = 26.1^\circ$ and 40.4° , which are defined by the lattice planes (101), (200), and (202) [3],[12]. The peaks around 19° and 40° indicate the semicrystalline nature of PVA [34],[35]. In the PVA-WH, PVA-H40, and PVA/gambir (0.5%) film samples with various heat treatment durations, there was a peak in the range of $2\theta = 10.8^\circ$ determined by the (100) lattice plane [2]. This peak indicates the crystalline region in PVA [36]. Based on the data in Table 2, the highest Crystallinity Index (CI) was observed in the PVA/gambir (0.5%)-H40 sample, with a value of 65.65%. PVA film samples with gambir extract had higher CI values than the pure PVA film samples. This increase in value is attributed to the polyphenol compounds in gambir, which contain many OH groups, enabling interaction with PVA OH groups via crosslinking. This interaction causes the polymer structure to become more regular and increase crystallinity [14].

On the other hand, the CI value percentage in the film sample increased after heat treatment. The increase in CI value can be attributed to intramolecular and intermolecular crosslinking that occurred as a result of the heat treatment. The crosslinking that occurred can make the formation of structural units more regular [3]. Moreover, the heat treatment applied can reduce the water content, thereby increasing crystallinity. This is confirmed by the study conducted by Xiang *et al.* [32], which shows that an increase in heat treatment duration (3-12 minutes) causes a decrease in the water content in the PVA film. The reduction in water content in the film can cause the chains between PVA molecules (through hydroxyl bonds) to become more regular, thereby increasing crystallinity. On the other hand,

increasing the duration of heat treatment (60 minutes) causes a decrease in the CI value of the sample. The decrease in CI value can be attributed to film degradation caused by excessive heat treatment duration, which can inhibit the formation of more regular structural units. Another study found that PVA film with a longer heat treatment duration can reduce the CI value from 88% (40 minutes of heat treatment) to 72.2% (60 minutes of heat treatment)[3].

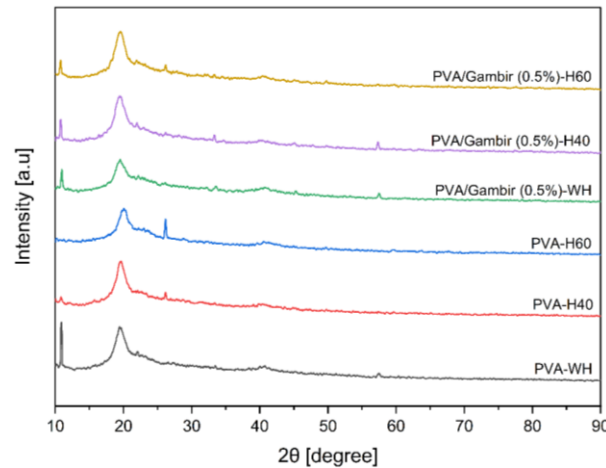


Fig. 4. XRD graph of PVA/gambir film samples

Table 2. Crystallinity index of PVA/gambir film samples

Sample name	Crystallinity index (CI) (%)
PVA-WH	50.02
PVA-H40	65.52
PVA-H60	59.63
PVA/gambir (0.5%)-WH	55.43
PVA/gambir (0.5%)-H40	65.65
PVA/gambir (0.5%)-H60	65.09

4. Identification of Hydrophilicity

Figure 5 shows the water contact angle of the pure PVA film sample and the PVA/gambir film with different heat treatment durations. Based on the histogram, it can be seen that all samples are hydrophilic materials. The hydrophilic material is a material that has a contact angle value in the range of $0^\circ < \theta < 90^\circ$, while the contact angle of the hydrophobic material is in the range of $90^\circ < \theta < 180^\circ$ [37]. The results of the water contact angle measurement show that pure PVA film increased from 22.99° (PVA-WH) to 39.52° (PVA-H60) after heat treatment. This increase also occurred in PVA films with the addition of gambir extract, namely from 18.45° (PVA/gambir (0.5%)-WH) to 41.80° (PVA/gambir (0.5%)-H60) after heat treatment (Figure 6). This indicates that hydrophobicity increases with increasing heat treatment duration. The increase in contact angle can be caused by an increase in polymer crosslinking, which results in a decrease in the quantity of hydrophilic -OH groups. A similar study by Rahmadiawan *et al.* [20], reported that heat treatment of PVA/gambir (1%) based films can increase hydrophobicity from 14° (without treatment) to 26° (40 minutes of heat treatment). In addition, the addition of gambir extract also affects the water contact angle value because the crosslinking process that occurs can increase the

intensity of hydrogen bonds between PVA chains, as well as between PVA chains and gambir, thereby reducing hydrophilicity. Two-way ANOVA analysis shows that the addition of gambir does not significantly affect hydrophilicity ($F(1,14) = 0$, p -value > 0.05), while the duration of heat treatment significantly affects hydrophilicity ($F(2,14) = 34.78$, p -value < 0.05).

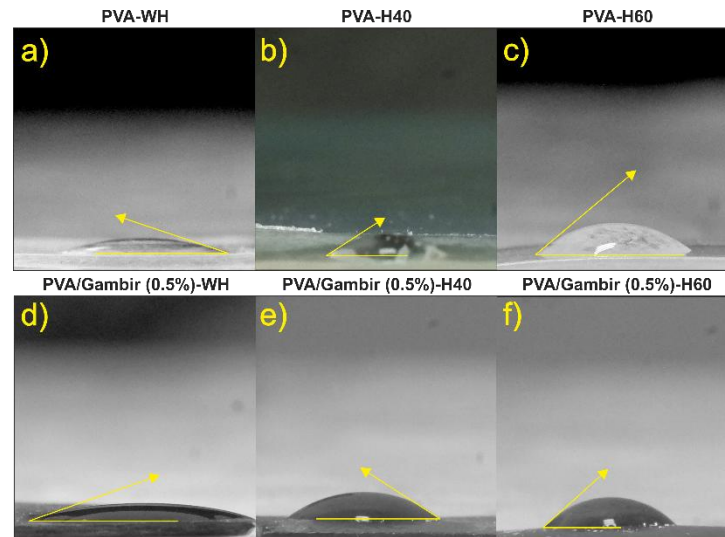


Fig. 5. Water contact angle of PVA/gambir film samples

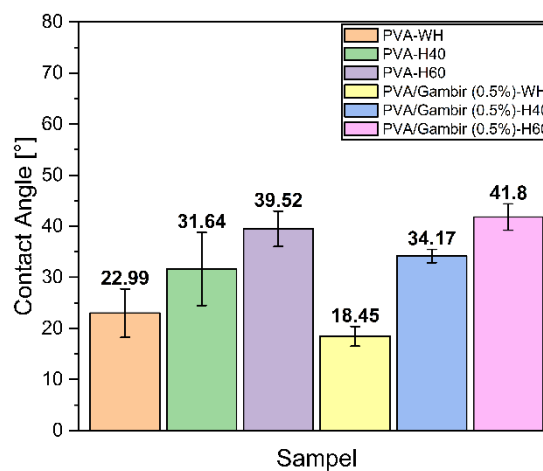


Fig. 6. Histogram of average values of water contact angle of PVA/gambir film samples

5. Identification of UV Protection

Figure 7 shows photographs of pure PVA and PVA/gambir film with different heat treatment durations. Pure PVA-WH, PVA-H40, and PVA-H60 films are visually the most transparent. The addition of gambir causes the film samples to turn yellow, but the university logo is still easily visible. The color change that occurred can be attributed to gambir, which contains tannin compounds. Tannin compounds can produce colors ranging from yellowish white to brown [23]. Figure 8 shows a graph of light transmission across a wavelength range of 200-1100 nm in pure PVA film samples and PVA/gambir films with different heat treatments. Based on Figure 8, the PVA/gambir film sample graph has the highest UV light absorption capacity.



Fig. 7. Photo of PVA/gambir film samples

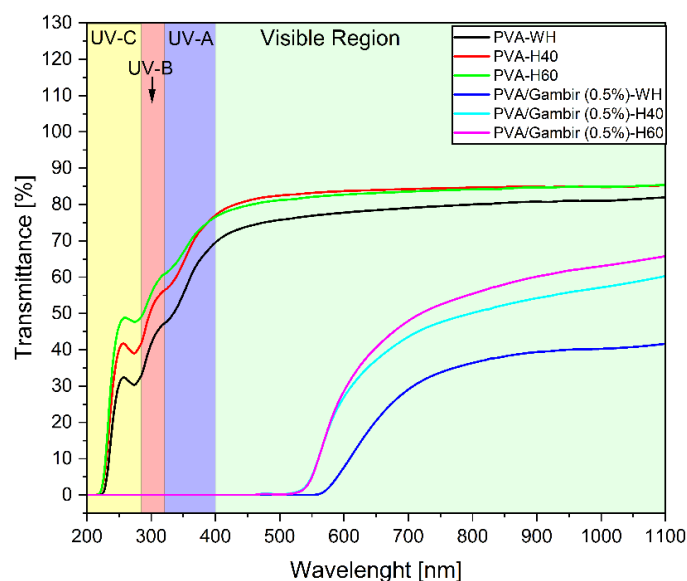


Fig. 8. Light transmission graph of PVA/Gambir film samples

PVA/gambir film samples have 100% UV absorption. The UV spectrum under sunlight is categorized into three types, namely UV-C (220-280 nm), UV-B (280-320 nm), and UV-A (320-400 nm) [38]. Figure 8 shows that all PVA/gambir film samples have UV-A protection, while all pure PVA film samples have UV-C protection. The improved UV protection can be associated with phenolic compounds derived from the catechin content in gambir. Phenolic compounds have a chromophore structure that can easily absorb UV radiation [39]. The UV protection properties derived from phenolic compounds can be obtained because of the ability to absorb certain wavelengths of light, causing the promotion of electrons to a higher energy level in their molecular structure. This ability comes from aromatic rings or conjugated double bonds that have strong absorption in the UV region [40]. These findings were proved by Zhai *et al.* [41], which shows that composite films containing tannins that include polyphenols have good UV light absorption. This indicates that a PVA film containing gambir extract can be used for packaging applications requiring UV protection, thereby extending food shelf life. In addition, heat treatment applied to all pure PVA film samples and PVA/gambir film samples did not significantly improve UV protection.

6. Identification of Biodegradable

Figure 9 shows the biodegradability histogram of the pure PVA film and PVA/gambir with different heat treatment durations. Based on the histogram, it is known that all samples show an increase in the average weight reduction value from the 4th day to the 16th day. The PVA/gambir (0.5%)-H40 film sample has the highest average weight reduction (biodegradable) value on the 16th day, which is 18.66%. PVA film samples with gambir addition had higher weight reduction values than the pure PVA film at each day. This can be attributed to gambir extract, which is a natural biomaterial. Natural biomaterials are susceptible to degradation, and the degradation process can damage the intermolecular polymer chains of PVA, thereby accelerating and hastening the degradation of PVA. Xu *et al.* [42] found that PVA films mixed with natural polyphenol compounds derived from tea had a higher biodegradation rate than pure PVA films. The film samples with a longer heat treatment duration (60 minutes) showed a decrease in percentage value on the 16th day compared to other samples. This may be because heat treatment can reduce the quantity of hydroxyl groups on the film surface, thus improving its hydrophobic properties [10]. Water and moisture in the soil activate the bacterial activities, which play an instrumental role in the degradation process [43]. The rate of biodegradation is influenced by the composition of the mixture of materials used by microorganisms, pH, temperature, oxygen, and particle size distribution in the soil [44]. Two-way ANOVA analysis shows that the addition of gambir ($F(1,65) = 203.57$, p -value < 0.05), heat treatment duration ($F(2,65) = 17.18$, p -value < 0.05), and day period ($F(3,65) = 26.09$, p -value < 0.05) have a significant effect on biodegradability.

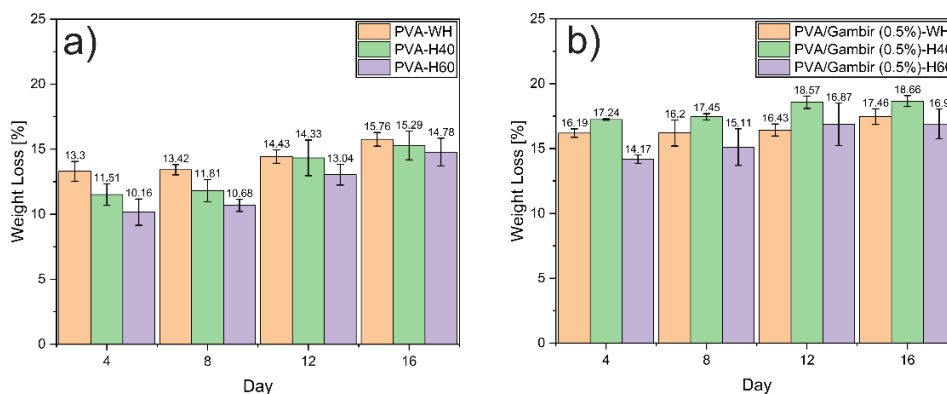


Fig. 9. Histogram of biodegradable film samples: a) pure PVA, b) PVA/gambir

7. Identification of Tensile Properties

Figure 10 shows the histogram of tensile strength and elongation in pure PVA and PVA/gambir films with different heat treatment durations. The PVA/gambir (0.5%)-H40 film sample has the highest tensile strength value of 47.82 N/mm² and elongation of 25.24%. The tensile strength and elongation values improved after the addition of gambir extract. This increase can be attributed to the interaction of PVA chains and phenolic compounds derived from gambir, which can reinforce the polymer network through hydrogen bonding. An increase in PVA-based films' tensile strength was also found after adding Bajakah Tampala extract as a source of phenolic compounds [45]. This is supported by the fact that the tannins contained in gambir extract can act as crosslinking agents due to their ability to form complex bonds and interact with polymer chains [15]. An increase in tensile strength also occurred in samples that were heat-treated for 40 minutes. This increase can be attributed to the density of cross-links that occurred in the film as a result of the heat

treatment [3]. Crosslinking can increase the mobility of polymer chains, causing changes in intramolecular and intermolecular interactions [46]. However, at a higher heat treatment duration (60 minutes), there was a decrease in tensile strength. This can be attributed to thermal degradation in the film due to the high heat treatment duration [3]. In addition, heat treatment causes an increase in elongation values along with an increase in heat treatment duration. This increase can be attributed to heat treatment, which can rearrange the PVA and PVA chains with gambir to form “physical anchors” that allow controlled stretching and ultimately result in an increase in elongation values before breaking [15]. Two-way ANOVA analysis shows that the addition of gambir ($F(1,14) = 1.37$, $p\text{-value} > 0.05$) and heat treatment ($F(2,14) = 1.22$, $p\text{-value} > 0.05$) have an effect but are not significant on tensile strength. Two-way ANOVA analysis shows that the addition of gambir ($F(1,14) = 0.04$, $p\text{-value} > 0.05$) has a significant but insignificant effect on elongation, while the duration of heat treatment ($F(1,14) = 4.03$, $p\text{-value} < 0.05$) has a significant effect on elongation.

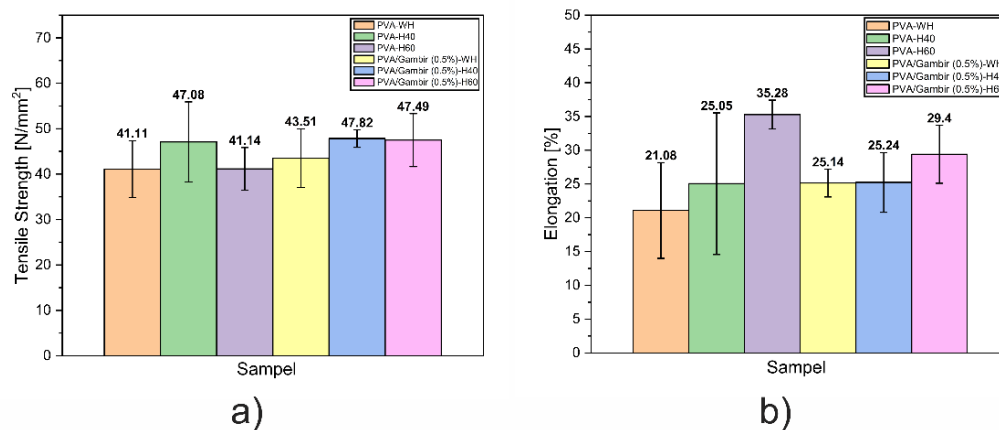


Fig. 10. Histogram of a) tensile strength, b) elongation of PVA/gambir film samples

IV. Conclusions

In this study, PVA films with added gambir extract concentrations (0.5%) and heat treatments (40 and 60 minutes) were reported. The PVA/gambir film obtained was analyzed to determine its surface morphology, functional groups, crystallinity index, hydrophilicity, UV protection, biodegradability, and tensile properties. The surface morphology of the PVA/gambir film became smoother and more homogenized as the heat treatment duration was increased. The addition of gambir to PVA film caused the formation of new functional groups, namely C-C and C-O, which originated from compounds contained in gambir. The crystallinity index of PVA/gambir film increased with increasing heat treatment duration up to 40 minutes. The hydrophilicity of the PVA/gambir film increased with increasing heat treatment duration. Statistical testing showed that the addition of gambir did not significantly affect hydrophilicity ($p\text{-value} > 0.05$), and heat treatment affected hydrophilicity ($p\text{-value} < 0.05$). PVA/gambir film has better UV (UV-A) protection compared to pure PVA film, but the duration of heat treatment does not significantly affect UV protection. Better UV protection can be attributed to the polyphenol compounds contained in gambir extract. PVA/gambir film with a heat treatment duration of 40 minutes showed the highest biodegradation rate of 18.66% in the 16th period. Statistical testing shows that the addition of gambir, the duration of heat treatment, and the time period have a significant effect on biodegradability ($p\text{-value} < 0.05$). The tensile properties of the PVA/gambir (0.5%)-H40 film sample had the highest tensile strength value of 47.82 N/mm² and elongation of 25.24%. However, the addition of gambir and the duration of heating did not significantly affect both

tensile strength (p-value > 0.05) and elongation (p-value > 0.05), but the duration of treatment did (p-value < 0.05). The findings indicate that the addition of gambir and heat treatment to PVA-based films can improve their characteristics and provide a solution for environmentally friendly and sustainable packaging.

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References

- [1] I.G.N. Santhiarsa, N.M. Dwidiani, I.G.N.P. Tenaya, and I.G.A. Negara, “Impact of natural polymer proportions on the fire-retardant properties of bioplastics,” *Journal of Mechanical Engineering Science and Technology (JMEST)*, vol. 8, no. 2, p. 434, 2024, doi: 10.17977/um016v8i22024p434.
- [2] E. Espinosa, I. Bascón-Villegas, A. Rosal, F. Pérez-Rodríguez, G. Chinga-Carrasco, and A. Rodríguez, “PVA/(ligno)nanocellulose biocomposite films. Effect of residual lignin content on structural, mechanical, barrier and antioxidant properties,” *International Journal of Biological Macromolecules*, vol. 141, pp. 197–206, 2019, doi: 10.1016/j.ijbiomac.2019.08.262.
- [3] S. Sau, S. Pandit, and S. Kundu, “Crosslinked poly (vinyl alcohol): Structural, optical and mechanical properties,” *Surfaces and Interfaces*, vol. 25, no. April, p. 101198, 2021, doi: 10.1016/j.surfin.2021.101198.
- [4] Y. Dou, E.A.M. Hassan, S. Wang, M.E. Gibril, and F. Kong, “Enhancing PVA mulching films: Leveraging modified lignin as a bio-based crosslinking agent for improved mechanical strength, UV barrier, and biodegradability,” *Industrial Crops & Products Journal*, vol. 222, no. P3, p. 119766, 2024, doi: 10.1016/j.indcrop.2024.119766.
- [5] S.A. Ali, A.N. Konwar, D. Thakur, and S. Kundu, “Metal (Ag)/metal oxide (CuO, ZnO)@polyvinyl alcohol (PVA) nanocomposite free-standing films: Physical and antimicrobial properties,” *Surfaces and Interfaces*, vol. 56, no. August 2024, p. 105587, 2025, doi: 10.1016/j.surfin.2024.105587.
- [6] J.I.T. Galarza, L.G.C. González, C. Luciani, and J.C.C. Torres, “Highly efficient caffeine-based PVA composite film for UV shielding,” *Carbon Trends*, p. 100502, 2025, doi: 10.1016/j.cartre.2025.100502.
- [7] J.R. Ansari, K. Park, and J. Seo, “Improving the oxygen barrier properties of composite films using green tea extracted CQDs and PVA for active packaging applications,” *Food Packaging and Shelf Life*, vol. 48, no. February, p. 101460, 2025, doi: 10.1016/j.fpsl.2025.101460.
- [8] Y. Wang, Y. Yu, C. Shi, Y. Ren, J. Han, and R. Wu, “Development of curcumin nanoparticle-modified photodynamic gelatin/PVA–chitosan bilayer films for preserving bigeye tuna,” *International Journal of Biological Macromolecules*, vol. 308, no. P4, p. 142299, 2025, doi: 10.1016/j.ijbiomac.2025.142299.
- [9] P. Kumar, R. Tanwar, V. Gupta, A. Upadhyay, A. Kumar, and K.K. Gaikwad, “Pineapple peel extract incorporated poly(vinyl alcohol)-corn starch film for active food packaging: Preparation, characterization and antioxidant activity,” *International Journal of Biological Macromolecules*, vol. 187, no. July, pp. 223–231, 2021, doi: 10.1016/j.ijbiomac.2021.07.136.
- [10] M. Sawant, T. Chakraborty, D. Yadav, S. Biranje, S. Saxena, and S. Shukla,

- “Stabilization strategies and optimization of polyvinyl alcohol-chitosan hybrid polymer,” *Hybrid Advances*, vol. 8, no. October 2024, p. 100345, 2025, doi: 10.1016/j.hybadv.2024.100345.
- [11] Z. Feng, D. Xu, Z. Shao, P. Zhu, J. Qiu, and L. Zhu, “Rice straw cellulose microfibril reinforcing PVA composite film of ultraviolet blocking through pre-crosslinking,” *Carbohydrate Polymers*, vol. 296, no. July, p. 119886, 2022, doi: 10.1016/j.carbpol.2022.119886.
- [12] H. Abrial, M. Ikhsan, D. Rahmadiawan, D. Handayani, N. Sandrawati, E. Sugiarti *et al.*, “Anti-UV, antibacterial, strong, and high thermal resistant polyvinyl alcohol/Uncaria gambir extract biocomposite film,” *Journal of Materials Research and Technology*, vol. 17, pp. 2193–2202, 2022, doi: 10.1016/j.jmrt.2022.01.120.
- [13] Miksusanti, A.N. Fithri, Herlina, D.P. Wijaya, and T. Taher, “Optimization of chitosan-tapioca starch composite as polymer in the formulation of gingival mucoadhesive patch film for delivery of gambier (*Uncaria gambir* Roxb) leaf extract,” *International Journal of Biological Macromolecules*, vol. 144, pp. 289–295, 2020, doi: 10.1016/j.ijbiomac.2019.12.086.
- [14] A. Labanni, Z. Zulhadjri, D. Handayani, Y. Ohya, and S. Arief, “The effect of monoethanolamine as stabilizing agent in *Uncaria gambir* Roxb. mediated synthesis of silver nanoparticles and its antibacterial activity,” *Journal of Dispersion Science and Technology*, vol. 41, no. 10, pp. 1480–1487, 2020, doi: 10.1080/01932691.2019.1626249.
- [15] D. Rahmadiawan, H. Abrial, I.C. Iby, H.-J. Kim, K.-H. Ryu, H.-W. Kwack *et al.*, “Effect of post-heat treatment on the UV transmittance, hydrophobicity, and tensile properties of PVA/*Uncaria gambir* extract blend films,” *Heliyon*, vol. 10, no. 10, p. e30748, 2024, doi: 10.1016/j.heliyon.2024.e30748.
- [16] Y. Guan, L. Shao, D. Dong, F. Wang, Y. Zhang, and Y. Wang, “Bio-inspired natural polyphenol crosslinking poly(vinyl alcohol) films with strong integrated strength and toughness,” *RSC Adv.*, vol. 6, no. 74, pp. 69966–69972, 2016, doi: 10.1039/c6ra08904f.
- [17] N. Zhang, L. Yang, H. Pan, S. Xing, J. Li, H. Song *et al.*, “Hydroxyl-crosslinked polyvinyl alcohol films reinforced with nanocellulose and tea polyphenols for antibacterial preservation of dried tofu,” *Internasional Journal of Biological Macromolecules*, vol. 323, p. 147157, 2025, doi: 10.1016/j.ijbiomac.2025.147157.
- [18] D. Rahmadiawan, H. Abrial, M.A. Pratama, H.-J. Kim, R.M. Railis, R. Kurniawan *et al.*, “Synergistic effects of *Uncaria gambir* and zinc oxide in polyvinyl alcohol films for enhanced UV and blue light shielding, antimicrobial properties, and hydrophobicity: improving application performance in sustainable packaging and protective eyewear,” *RSC Advances*, vol. 15, no. 4, pp. 2766–2778, 2025, doi: 10.1039/d4ra08801h.
- [19] N.H.N. Mohamed, H. Takagi, and A.N. Nakagaito, “Mechanical properties of heat-treated cellulose nanofiber-reinforced polyvinyl alcohol nanocomposite,” *Journal of Composite Materials*, vol. 51, no. 14, pp. 1971–1977, 2017, doi: 10.1177/0021998316665238.
- [20] D. Rahmadiawan, H. Abrial, S. Shi, T. Huang, and R. Zainul, “Tribological properties of polyvinyl alcohol/*uncaria gambir* extract composite as potential green protective film,” *Tribology in Industry*, vol. 45, no. 2, pp. 367–374, 2023, doi: 10.24874/ti.1482.05.23.06.
- [21] O.W. Guirguis and M.T.H. Moselhey, “Thermal and structural studies of poly (vinyl alcohol) and hydroxypropyl cellulose blends,” *Natural Science*, vol. 04, no. 01, pp.

- 57–67, 2012, doi: 10.4236/ns.2012.41009.
- [22] N. Chousidis, “Polyvinyl alcohol (PVA)-based films: Insights from crosslinking and plasticizer incorporation,” *Engineering Research Express*, 2024, doi: 10.1088/2631-8695/ad4cb4.
- [23] M. Ismayati, N.A.N. Fatah, E.E. Ernawati, Juliandri, W.B. Kusumaningrum, M.A.R. Lubis *et al.*, “Antioxidant and UV-blocking activity of PVA/tannin-based bioplastics in food packaging application,” *International Journal of Biological Macromolecules*, vol. 257, no. P2, p. 128332, 2024, doi: 10.1016/j.ijbiomac.2023.128332.
- [24] A.K. Yontar, S. Çevik, and O. Yontar, “Green production of plant/collagen-based antibacterial polyvinyl alcohol (PVA) nanocomposite films,” *Sustainable Chemistry and Pharmacy*, vol. 33, no. May, p. 101119, 2023, doi: 10.1016/j.scp.2023.101119.
- [25] J. Wang, C. Chen, and J. Xie, “Loading oregano essential oil into microporous starch to develop starch/polyvinyl alcohol slow-release film towards sustainable active packaging for sea bass (*Lateolabrax japonicus*),” *Industrial Crops and Products*, vol. 188, no. PB, p. 115679, 2022, doi: 10.1016/j.indcrop.2022.115679.
- [26] R.M. Chuang, T.H. Vo, H.K. Tsao, and Y.J. Sheng, “High-strength poly(vinyl alcohol) physical eutectogels: Effects of polymer molecular weight, DES composition, and heat treatment,” *Journal of Molecular Liquids*, vol. 417, no. August 2024, p. 126592, 2025, doi: 10.1016/j.molliq.2024.126592.
- [27] Z. Xie, M. Hoang, D. Ng, C. Doherty, A. Hill, and S. Gray, “Effect of heat treatment on pervaporation separation of aqueous salt solution using hybrid PVA/MA/TEOS membrane,” *Separation and Purification Technology*, vol. 127, pp. 10–17, 2014, doi: 10.1016/j.seppur.2014.02.025.
- [28] K. Park, Y. Oh, P.K. Panda, and J. Seo, “Effects of an acidic catalyst on the barrier and water resistance properties of crosslinked poly (vinyl alcohol) and boric acid films,” *Progress in Organic Coatings*, vol. 173, no. September, p. 107186, 2022, doi: 10.1016/j.porgcoat.2022.107186.
- [29] Z. Bai, T. Wang, X. Zheng, Y. Huang, Y. Chen, and W. Dan, “High strength and bioactivity polyvinyl alcohol/collagen composite hydrogel with tannic acid as cross-linker,” *Polymer Engineering and Science*, vol. 61, no. 1, pp. 278–287, 2021, doi: 10.1002/pen.25574.
- [30] E. Caló, J.M.S.D. Barros, M. Fernández-Gutiérrez, J. San Román, L. Ballamy, and V.V. Khutoryanskiy, “Antimicrobial hydrogels based on autoclaved poly(vinyl alcohol) and poly(methyl vinyl ether-alt maleic anhydride) mixtures for wound care applications,” *RSC Advances*, vol. 6, no. 60, pp. 55211–55219, 2016, doi: 10.1039/c6ra08234c.
- [31] S. Shiyan, “FTIR spectroscopy combined with chemometrics for evaluation of gambir extract – self nano emulsifying formulation from *Uncaria gambir* Roxb,” *Biointerface Research in Applied Chemistry*, vol. 13, no. 2, pp. 1–11, 2023, doi:10.33263/BRIAC132.153.
- [32] A. Xiang, C. Lv, and H. Zhou, “Changes in crystallization behaviors of poly(vinyl alcohol) induced by water content,” *Journal of Vinyl and Additive Technology*, vol. 26, no. 4, pp. 613–622, 2020, doi: 10.1002/vnl.21775.
- [33] A. Morales, M.Á. Andrés, J. Labidi, and P. Gullón, “UV–vis protective poly(vinyl alcohol)/bio-oil innovative films,” *Industrial Crops and Products*, vol. 131, no. July 2018, pp. 281–292, 2019, doi: 10.1016/j.indcrop.2019.01.071.
- [34] A. Bouzidi, W. Jilani, T.H. AlAbdulaal, M. Jalalah, F.A. Harraz, I.S. Yahia *et al.*, “Simple synthesis and characterization of novel polyvinyl alcohol capped sodium selenite solid composite film (PVA: NaSe SCF) samples,” *Journal of Science:*

- Advanced Materials and Devices*, vol. 7, no. 3, p. 100458, 2022, doi: 10.1016/j.jsamd.2022.100458.
- [35] A. Atta, K. Alshammari, A.H. Alanazi, T. Alashgai, and M.M. Abdelhamied, "Fabrication, surface characterization and optical behavior of flexible PVA/Nd₂O₃ polymer nanocomposites materials for optoelectronics applications," *Inorganic Chemistry Communications*, vol. 170, no. P1, p. 113249, 2024, doi: 10.1016/j.inoche.2024.113249.
- [36] Q. He, Y.-Q. Fang, Y. Han, W.-N. Qin, J.-K. Nie, D. Hou *et al.*, "Novel synthesis of PVA/NaCl hydrogel for reversible thermochromism," *Optical Materials*, vol. 132, no. March, p. 112754, 2022, doi: 10.1016/j.optmat.2022.112754.
- [37] M.R. Suhasini, K.M. Rajeshwari, S. Bindya, A.B. Hemavathi, P. Vishwanath, A. Syed *et al.*, "Pectin/PVA and pectin-MgO/PVA films: Preparation, characterization and biodegradation studies," *Heliyon*, vol. 9, no. 5, p. e15792, 2023, doi: 10.1016/j.heliyon.2023.e15792.
- [38] Y. Wang, T. Li, H. Bai, M. Chen, Y. Xie, and W. Dong, "Simultaneous enhancements of uv-shielding properties and photostability of poly(vinyl alcohol) via incorporation of Sepia eumelanin," *ACS Sustainable Chemistry & Engineering*, 2016, doi: 10.1021/acssuschemeng.5b01734.
- [39] S. Tripathi, P. Kumar, and K.K. Gaikwad, "UV- shielding and antioxidant properties of chitosan film impregnated with Acacia catechu modified with calcium carbonate for food packaging," *International Journal of Biological Macromolecules*, vol. 257, no. P2, p. 128790, 2024, doi: 10.1016/j.ijbiomac.2023.128790.
- [40] M. Alizadeh Sani, A. Khezerlou, M. Tavassoli, A.H. Abedini, and D.J. Mc Clements, "Development of sustainable UV-screening food packaging materials: A review of recent advances," *Trends in Food Science and Technology*, vol. 145, no. February, p. 104366, 2024, doi: 10.1016/j.tifs.2024.104366.
- [41] Y. Zhai, J. Wang, H. Wang, T. Song, W. Hu, and S. Li, "Preparation and characterization of antioxidative and UV-protective larch bark tannin/PVA composite membranes," *Molecules*, vol. 23, no. 8, 2018, doi: 10.3390/molecules23082073.
- [42] X.-J. Xu, S.-M. Huang, and L.-H. Zhang, "Biodegradability, antibacterial properties, and ultraviolet protection of polyvinyl alcohol natural polyphenol blends," *Polymers and Polymer Composites*, vol. 16, no. 2, pp. 101–113, 2008, doi: 10.1002/pc.
- [43] R. Hussain, S.A. Batool, A. Aizaz, M. Abbas, and M.A. Ur Rehman, "Biodegradable packaging based on poly(vinyl alcohol) and carboxymethyl cellulose films incorporated with ascorbic acid for food packaging applications," *ACS Omega*, vol. 8, no. 45, pp. 42301–42310, 2023, doi: 10.1021/acsomega.3c04397.
- [44] I. Korbag and S. Mohamed Saleh, "Studies on mechanical and biodegradability properties of PVA/lignin blend films," *International Journal of Environmental Studies*, vol. 73, no. 1, pp. 18–24, 2016, doi: 10.1080/00207233.2015.1082249.
- [45] Kadriadi, D. Rahmadiawan, H. Abral, Ilhamdi, M. Ivan, Akmal *et al.*, "A novel active packaging film based on polyvinyl alcohol/bajakah tampala (*Spatholobus littoralis* hassk) extract: Enhancing mechanical, UV protection, thermal stability, antimicrobial, and barrier properties," *Food Bioscience*, vol. 68, no. April, p. 106500, 2025, doi: 10.1016/j.fbio.2025.106500.
- [46] A. Bozdoğan, B. Aksakal, U. Şahintürk, and Ö. Yargı, "Influence of heating on spectroscopic, mechanical, and thermal properties of reduced graphene oxide-poly(vinyl alcohol) composite films," *Journal of Molecular Structure*, vol. 1174, pp. 133–141, 2018, doi: 10.1016/j.molstruc.2018.06.011.