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Eco-friendly bio-nanocomposite films for sustainable packaging

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ABSTRACT

This study explores synthesizing bio-nanocomposite films using chitosan nanoparticles, elephant yam (*Amorphophallus paeoniifolius*) starch, and butterfly pea (*Clitoria ternatea*) extract as an antioxidant. The films were characterized to assess their structural, thermal, and functional properties for potential applications in sustainable packaging. Fourier transform infrared spectroscopy (FTIR) revealed enhanced hydrogen bonding between anthocyanins and the matrix, indicated by increased intensity of the broadband at 3300–3400 cm^{-1} and pronounced C=O stretching peaks at 1640–1650 cm^{-1} with higher butterfly pea concentrations. Differential scanning calorimetry (DSC) showed increased glass transition temperature (T_g) with anthocyanin addition, reflecting reduced polymer chain mobility due to hydrogen bonding and π-π interactions. Minor variations in melting temperature (T_m) suggest a balance between amorphous and crystalline phases at higher anthocyanin concentrations. Functional analyses indicated that 15% anthocyanin concentration improved UV barrier properties and antioxidant activity but slightly increased water vapor permeability, while water uptake showed minimal change. These findings demonstrate that integrating butterfly pea extract enhances the performance of bio-nanocomposite films, making them promising candidates for eco-friendly packaging applications.

Keywords: elephant yam starch, chitosan nanoparticle, butterfly pea anthocyanin, bio-nanocomposite.

INTRODUCTION

The growing demand for sustainable and eco-friendly materials has led to the exploration of bio-based films, particularly in packaging applications, as alternatives to conventional synthetic plastics (Gamage et al., 2024; Rachmina et al., 2024). Bio-nanocomposite films, made from natural polymers, offer a promising solution due to their biodegradability, renewability, and reduced environmental impact (Moshood et al., 2022). Among these, chitosan, a biopolymer derived from chitin, has garnered considerable attention for its excellent film-forming ability, antimicrobial properties, and biodegradability. However, despite these advantages, chitosan films suffer inherent drawbacks, including brittleness, poor mechanical strength, and limited flexibility (Chauchan et al., 2024). These limitations necessitate the incorporation of additional materials to improve their performance, and starch, a natural polysaccharide, is commonly used as a reinforcing agent.

Elephant yam (*Amorphophallus paeoniifolius*) starch, a rich source of carbohydrates, is particularly suitable for bio-nanocomposite films due to its favorable film-forming properties (Arifin et al., 2023). However, like many starches, elephant yam starch faces challenges such as high moisture sensitivity, poor mechanical strength, and inadequate thermal stability, which limit its effectiveness when used alone (Singh et al., 2022). The integration of elephant yam starch with chitosan addresses these issues, enhancing the overall mechanical, barrier, and thermal properties of the bio-nanocomposite (Liu et al., 2024). The synthesis of bio-composite films from chitosan and starch has garnered significant attention in recent years due to their potential applications in sustainable food packaging. Hasan et al. (2022) developed an active film using corn starch and chitosan, enhanced with clove oil, demonstrating promising functional properties. Similarly, Priyanka et al. (2024) crafted an active food packaging material from a polymeric blend of starch, chitosan, and taro mucilage enriched with ZnO nanoparticles. The resulting film exhibited notable antibacterial efficacy against food spoilage pathogens. Furthermore, the integration of tartaric acid (TA) and citric acid (CA) as natural plasticizers in starch/pectin and chitosan blend bioplastic films has been explored, as reported by Arooj et al. (2024). These studies revealed that bioplastics possess essential characteristics such as biodegradability, mechanical strength, and non-phytotoxicity, supported by FTIR and XRD analyses showing amide/ester linkages and amorphous properties. Such bio-derived films hold great potential for addressing the growing demand for eco-friendly food packaging materials.

While the development of bio-composite films for food packaging has attracted considerable attention, there remains a notable scarcity of studies focusing on the incorporation of chitosan nanoparticles enriched with butterfly pea anthocyanins as antioxidants. This innovative approach not only leverages the natural bioactivity of anthocyanins but also addresses the pressing need for sustainable, functional packaging materials with enhanced antioxidant properties A key novelty of this research lies in the use of chitosan nanoparticles as an alternative to conventional chitosan. Chitosan nanoparticles, owing to their smaller size and larger surface area, exhibit superior properties in bio-nanocomposite films, such as enhanced mechanical strength, improved flexibility, and better interactions with other matrix components (Jha & Mayanovic, 2023). The use of nanoparticles offers a significant improvement over traditional chitosan, potentially overcoming its limitations and leading to the development of more durable, flexible, and functional films for a variety of applications (Yanat & Schroën, 2021).

Moreover, this study introduces a novel approach by incorporating butterfly pea (*Clitoria ternatea*) extract, a natural source of anthocyanins, into the bio-nanocomposite films. Butterfly pea extract not only imparts antioxidant properties but also enhances the films' UV-barrier capabilities. The incorporation of anthocyanins as an active ingredient offers a unique way to improve the stability and shelf life of packaged products, particularly in food packaging, where oxidative degradation and UV exposure are critical concerns (Eghbaljoo et al., 2023). The combination of chitosan nanoparticles, elephant yam starch, and butterfly pea anthocyanins is an innovative approach that has not been widely explored, making this study a unique contribution to the field of bio-nanocomposite materials.

This research aims to explore the effects of varying concentrations of butterfly pea extract (0%, 5%, 10%, and 15%) on the structural, thermal, and functional properties of chitosan nanoparticle-based bio-nanocomposite films. The films are characterized in terms of Fourier transform infrared spectroscopy (FTIR), differential scanning calorimetry (DSC), water uptake, water vapor permeability, UV-barrier, and antioxidant activity, offering a comprehensive understanding of their potential for use in sustainable packaging solutions.

EXPERIMENTAL

Materials

EYS (amylose: 24.5%; amylopectin: 75.5%) was obtained in Aceh, Indonesia, processed, and soaked in water for 24 hours. Chimultiguna Co., Ltd. (Indramayu, Indonesia) supplied CH powder (particle size: 200-300 mesh; molecular mass: 102 KDa; deacetylation degree: 96.24%). Chitosan nanoparticles were obtained after further processing using a planetary ball mill (DECO-PBM-V-0.4, China) for 70 hours, resulting in particles with an average size of approximately 130 nm. 2,2-Diphenyl-1-picrylhydrazyl (DPPH), glycerol, and glacial acetic acid were purchased from Sigma Aldrich (Darmstadt, Germany). The butterfly pea (BP) flowers were purchased at a local market in Banda Aceh, Indonesia.

Film preparation

Films were manufactured using a solvent-casting approach developed by (Hasan et al., 2022). Film-forming solutions comprising 3% w/v CH/EYS and BP were developed to produce four different film bio-nanocomposites. The control film, CH/EYS, was composed of 60% CH and 40% EYS (w/w), with no BP, as a plasticizer, 30% glycerol was added. Dissolving EYS powder in a 1.5% acetic acid solution and agitating for 45 minutes yielded a 3% w/v EYS solution. By combining CH nanoparticles in 30 mL of

1.5% acetic acid and agitating for 45 minutes, a 3% w/v CH solution was obtained. The bio-nanocomposite film was created by combining CH and EYS solutions with BP (0–15% w/w) as an antioxidant**.** The blend underwent stirring on a hotplate maintained at 90 °C. Following a 3-hour interval, each solution was carefully poured onto a 10-cm-diameter acrylic plate, allowed to cool to room temperature, and subsequently stored for 36 hours in a controlled environment at 22°C with a relative humidity of 55 ± 2%. Films with different BP concentrations (0–15 wt%) were labeled as CH/EYS, CH/EYS-BP5%, CH/EYS-BP10%, and CH/EYS-BP15%.

Fourier transform infrared spectroscopy

FTIR spectra were measured to evaluate the structure of bio-nanocomposite films that contribute to their mechanical, thermal, and barrier properties. Samples were cut into 2×2 cm films and attached to sample holders. Subsequently, measurements were carried out with an FTIR spectrometer (Cary 630, Agilent Technologies, USA) in the wavenumber range of 600–4000 cm^{-1} at a resolution of 4 cm^{-1}.

Differential scanning calorimetry analysis

The thermal properties of the biocomposite films were analyzed using differential scanning calorimetry (DSC) (PT 1600 simultaneous thermogravimetric analyzer, Linseis Inc., USA) to determine their thermal stability and phase transition characteristics. DSC was employed to evaluate the glass transition temperature (T_g) and melting temperature (T_m) of the bio-nanocomposite films. Approximately 5–10 mg of each film sample was accurately weighed and sealed in an aluminum pan, with an empty aluminum pan used as a reference. The samples were heated from 30°C to 600 °C at a rate of 10 °C/min under a nitrogen atmosphere with a flow rate of 50 mL/min to prevent oxidation and ensure an inert environment.

Water uptake and water vapor permeability

The water uptake of the bio-nanocomposite films was determined using a gravimetric method under controlled conditions. Film samples were cut into uniform rectangular pieces (e.g., 2×2 cm), and their initial dry weights (W_0) were measured with an analytical balance. The samples were then immersed in distilled water at room temperature and incubated for a predetermined duration, such as 24 hours. After immersion, the films were gently removed, and surface water was blotted using filter paper to ensure that only absorbed water was measured. The wet weights (W_1) of the films were recorded immediately after blotting. Water uptake was calculated using the formula (Eq. 1).

$$Water\ uptake\ (\%) = \frac{w_1 - W_0}{W_0} \times 100 \quad (1)$$

where: W_0 and W_1 are the initial dry weight and wet weight, respectively. Each measurement was performed in triplicate for accuracy and reproducibility.

The water vapor permeability (WVP) of the films was determined gravimetrically referred to the procedure developed by (Hermawan et al., 2019). 7 mm film samples were sealed securely onto a permeation container filled with distilled water (RH = 100%) at a 3/4 level from the film. After being weighed, these permeation cells were placed in desiccators filled with granular anhydrous calcium chloride at 50% RH and 25°C. The experiment, which was conducted in triplicate for each film sample, involved weighing the cells every hour for up to 6 hours (Eq. 2) was used to compute the water vapor permeability (WVP):

$$WVP\ (gPa^{-1}s^{-1}m^{-1}) = \frac{WVTR\ \times\ L}{\Delta P} \quad (2)$$

where: L is the thickness of the film and P is the difference in pressures applied on the desiccator and test cup (P = 3169 Pa) (Karimi Sani et al., 2019).

Antioxidant activity

The antioxidant activity of the biocomposite films was assessed based on their ability to scavenge DPPH (2,2-diphenyl-1-picrylhydrazyl) radicals. A 0.1-mM DPPH solution was prepared by dissolving 1.97 mg of DPPH in 50 mL of ethanol and stored in an amber bottle to protect it from light.

For the analysis, 50 mg of each film sample was weighed and added to 10 mL of 96% ethanol. The mixture was vortexed for 1 minute to ensure thorough extraction. A volume of 4.0 mL of the prepared DPPH solution was then mixed with 1.0 mL of the film extract, and the resulting solution was incubated in the dark for 30 minutes to prevent photodegradation of the radical species. The absorbance of the solution was measured at 517 nm using a UV–Vis spectrophotometer. The antioxidant activity, expressed as the DPPH radical scavenging percentage, was calculated using the following formula:

$$Antioxidant\ activity\ (\%) = \frac{A_0 - A_1}{A_0} \times 100 \quad (3)$$

X-ray diffraction

The XRD structure patterns of films were obtained using an X-ray diffractometer (Shimadzu, Japan) adjusted at 45 kV and 30 mA. The machine was fitted with Cu Kα radiation with a wavelength of 0.15418 nm. At room temperature, samples were scanned over the diffraction angle 2θ = 5–80° range at a rate of 1°/min.

UV barrier

The UV-barrier properties of the bio-nanocomposite films were evaluated to determine their potential in food packaging applications, particularly their ability to protect contents from harmful ultraviolet (UV) radiation. The UV transmittance was measured using a UV-visible spectrophotometer within the wavelength range of 200–800 nm. The bio-nanocomposite film samples were cut into square pieces of uniform size, and their transmittance spectra were recorded in the spectral region corresponding to UV light absorption.

Statistical analysis

One-way ANOVA was used to assess differences among groups, followed by Tukey's HSD test for pairwise comparisons. Results are presented as mean ± standard deviation, with significance level at $p < 0.05$.

RESULT AND DISCUSSION

Fourier transform infrared spectroscopy analysis

The FTIR spectra of chitosan/elephant yam starch (CH/EYS) biocomposite films with varying concentrations of butterfly pea (BP) anthocyanin extract (0%, 5%, 10%, and 15%) provide insights into the molecular interactions and structural modifications induced by the incorporation of anthocyanins. The characteristic peaks observed in the spectra correspond to functional groups inherent in the bio-nanocomposite matrix and the anthocyanin extract. The control sample (CH/EYS without BP) displays typical absorption bands for chitosan and starch, including the broad peak at approximately 3300–3400 cm^{-1}, attributed to O-H and N-H stretching vibrations, and the peaks around 2900 cm^{-1} due to C-H stretching vibrations (Arcana et al., 2010). Upon the addition of BP anthocyanin extract, notable changes were observed in the fingerprint region and the hydrogen-bonding region. The intensity of the broadband at 3300–3400 cm^{-1} increases with BP concentration, suggesting enhanced hydrogen bonding between anthocyanins and the matrix. Additionally, the peaks at around 1640–1650 cm^{-1}, corresponding to C=O stretching of amide groups and conjugated anthocyanins, become more pronounced with increasing BP content. This indicates the successful integration of anthocyanins into the bio-nanocomposite, potentially through non-covalent interactions (Pang et al., 2023).

The FTIR results corroborate the antioxidant activity data, indicating strong interactions between the anthocyanins and the chitosan/starch matrix (Figure 1). These interactions enhance the structural integrity of the films while maintaining the bioactivity of the anthocyanins (Zhu et al., 2023). The presence of aromatic C=C bonds and carbonyl groups from anthocyanins indicates their potential role as active sites for radical scavenging, further supporting the observed increase in antioxidant activity (Dudek et al., 2022). The integration of BP anthocyanins into the CH/EYS matrix also suggests potential applications in active food packaging, where such films could provide antioxidative and UV-protective functions. The spectral changes observed highlight the compatibility of the anthocyanins with the biopolymer matrix, making these films suitable for use as active and intelligent packaging materials.

Differential scanning calorimetry

The DSC analysis of chitosan/elephant yam starch-based bio-nanocomposite films with varying concentrations of butterfly pea anthocyanin extract (0%, 5%, 10%, and 15%) revealed significant changes in their thermal properties. The glass transition temperature (T_g) increased with higher anthocyanin concentrations, indicating enhanced molecular interactions such as hydrogen bonding and π-π interactions between the anthocyanins and the functional groups within

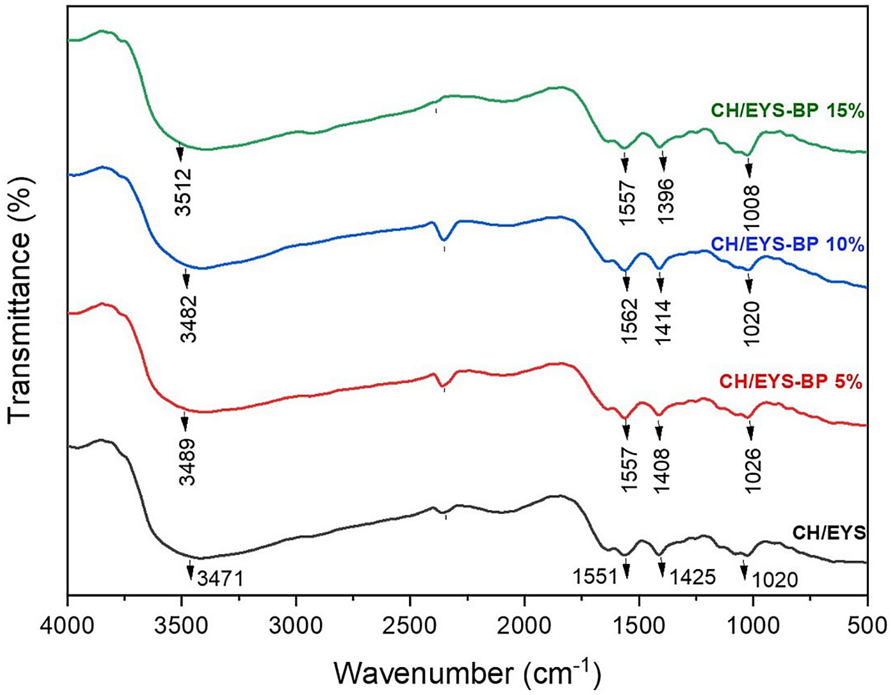

Figure 1. FTIR spectral profile of chitosan/starch-based bio-nanocomposite films

the chitosan/starch matrix (Kareem et al., 2019). This behavior parallels observations in graphene nanoplatelet (GNP)-reinforced PVC composites, where the incorporation of nanofillers significantly enhanced Tg by improving interfacial bonding and limiting segmental relaxation (Mindivan et al., 2020, 2024). This increase in T_g reflects reduced polymer chain mobility due to the successful integration of anthocyanins into the bio-nanocomposite matrix (Almasi et al., 2022). Furthermore, the melting temperature (T_m) exhibited slight variations, with a minor decrease observed at low anthocyanin content (5%), suggesting a reduction in crystalline regions. At higher concentrations (10% and 15%), T_m stabilized, indicating a balanced distribution of anthocyanins, which promotes equilibrium between the amorphous and crystalline phases (Wang et al., 2024). These findings are consistent with studies on polymer nanocomposites where fillers act as nucleating agents, influencing the crystalline morphology and thermal transitions (Mindivan et al., 2020).

The incorporation of anthocyanins not only reinforces the structural network of the chitosan/starch matrix through non-covalent interactions but also protects against thermal degradation. These results demonstrate that the addition of butterfly pea anthocyanin extracts not only improves the thermal stability of the bio-nanocomposite films but also contributes to enhanced functional properties, such as antioxidant activity, UV barrier capability, and antimicrobial performance (Khanifah et al., 2023). Such improvements corroborate with studies showing increased residue formation in polymer composites due to well-dispersed fillers (Mindivan et al., 2020). The incorporation of butterfly pea flower anthocyanin into biopolymer films has been reported to enhance their functional properties significantly. Anugrah et al. (2023) demonstrated that anthocyanin incorporation imparts antioxidant and antimicrobial activities to the films, while also improving their UV–Vis light barrier capabilities, thus making them suitable for active packaging applications. Similarly Wu et al. (2025) highlighted that anthocyanin addition improves the light-blocking ability and introduces a pH-responsive characteristic to the films. Similar results have also been demonstrated in our previous study (Hasan et al., 2024). These findings underscore the dual functionality of anthocyanin as both a bioactive and structural enhancer, presenting a promising avenue for the development of smart and sustainable food packaging materials. The combination of chitosan, Elephant yam starch, and anthocyanins produces bio-nanocomposite films with high potential for applications in active packaging and smart sensors requiring thermal resistance.

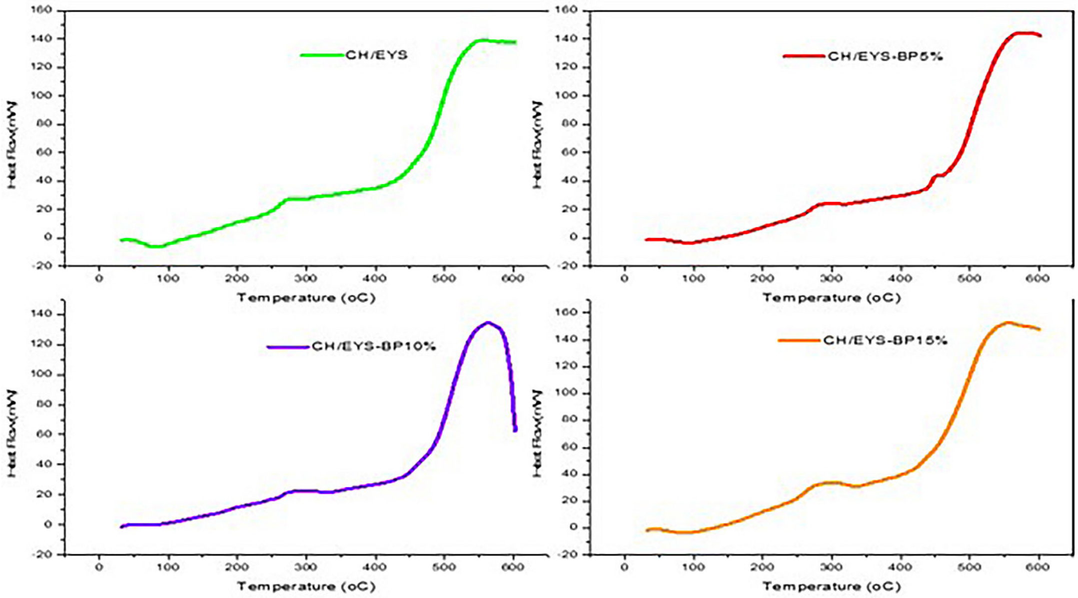

Figure 2. DSC analysis of biocomposite films: (a) CH/EYS, (b) CH/EYS-BP5%, (c) CH/EYS-BP10%, (d) CH/EYS-BP15%

Water uptake and water vapor permeability

The water vapor permeability (WVP) of the bio-nanocomposite films, as shown in Figure 3 (a), exhibited a decreasing trend with the incorporation of butterfly pea anthocyanin extract as an antioxidant. The CH/EYS film without BP showed the highest WVP value, indicating its greater susceptibility to moisture transfer. The addition of BP at 5%, 10%, and 15% concentrations resulted in reduced WVP, with the CH/EYS-BP10% film achieving the lowest permeability value. This decrease can be attributed to the interaction between the BP phenolic compounds and the polymer matrix, which enhances the hydrophobicity and reduces the water vapor diffusion rate. However, at 15% BP concentration, a slight increase in WVP was observed, possibly due to the disruption of polymer chain interactions caused by excessive BP loading.

The water uptake capacity of the bio-nanocomposite films, as illustrated in Figure 3b, varied significantly with BP concentration. The CH/EYS film exhibited the lowest water uptake, demonstrating its relatively higher resistance to water absorption. The addition of BP at 5% and 10% concentrations did not significantly alter the water uptake compared to the CH/EYS control film. However, at 15% BP concentration, the water uptake increased markedly. This increase is likely due to the hydrophilic nature of BP, which enhances the film's ability to absorb water as its concentration increases beyond a certain threshold. The presence of excess BP could also disrupt

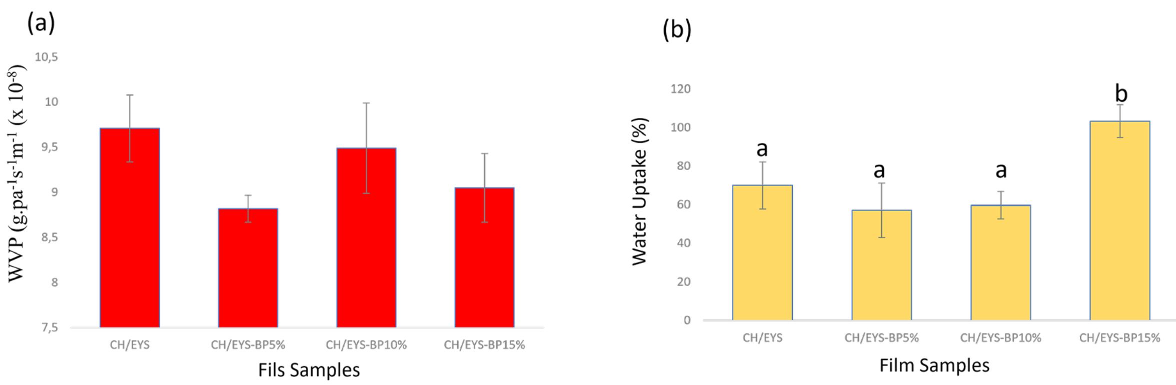

Figure 3. Effect of BP concentration on water vapor permeability and water uptake of CH/EYS films

the uniformity of the polymer matrix, creating interstitial spaces that facilitate water penetration (Zhou et al., 2024). The incorporation of butterfly pea flower anthocyanin into chitosan/starch matrices results in a decreased water vapor permeability (WVP) due to several synergistic interactions. Anthocyanins, with their hydroxyl groups, form hydrogen bonds or electrostatic interactions with chitosan's amino groups and starch's hydroxyl groups, strengthening the polymer network and reducing free volume. Additionally, the hydrophobic components of anthocyanins enhance the hydrophobicity of the film, further limiting water vapor diffusion. The filler effect of anthocyanins also reduces porosity, creating more tortuous diffusion pathways (Hermawan et al., 2019). Furthermore, the presence of anthocyanins may increase the crystallinity of the film matrix, leading to a more organized structure that inhibits moisture transport (Kumar et al., 2024). Lastly, pH modulation by anthocyanins and potential cross-linking effects contribute to a denser, less permeable film structure. These interactions collectively enhance the barrier properties of the composite film. However, contrasting results have been reported by Li et al. (2024), where the interaction through hydrogen bonding between anthocyanins and the polymer matrix was found to increase the water vapor permeability (WVP).

Antioxidant activity

The antioxidant activity of chitosan/Elephant yam starch (CH/EYS) bio-nanocomposite films was evaluated, and the results reveal a significant enhancement with the incorporation of butterfly pea anthocyanin extract (Figure 4). The control sample (0% BP) exhibited an antioxidant activity of 23.61%, reflecting the inherent antioxidant properties of the chitosan and starch matrix. However, the addition of BP extract markedly increased the antioxidant activity, reaching 27.85%, 44.85%, and 82.62% for films containing 5%, 10%, and 15% BP, respectively.

This progressive increase in antioxidant activity can be attributed to the rich anthocyanin content of butterfly pea extract, which is known for its potent radical scavenging ability (Juswardi et al., 2023). Anthocyanins, as phenolic compounds, contribute free hydroxyl groups that interact with free radicals, thereby inhibiting oxidative reactions (Lu et al., 2024). The steep rise in antioxidant activity at higher BP concentrations (10% and 15%) suggests a cumulative effect of the anthocyanin molecules, resulting in a significant enhancement of the film's antioxidant properties.

The data indicate that the incorporation of BP extract not only enhances the film's antioxidant activity but also broadens its potential application as an active packaging material. Films with high antioxidant activity, such as those containing 15% BP extract, can effectively mitigate oxidative degradation in food products, prolonging shelf life and maintaining nutritional quality. This aligns with previous studies emphasizing the role of phenolic additives in developing functional biopolymer films with active properties (Hasan et al., 2022). Furthermore, the results highlight the versatility of the CH/EYS matrix as a carrier for bioactive compounds like anthocyanins.

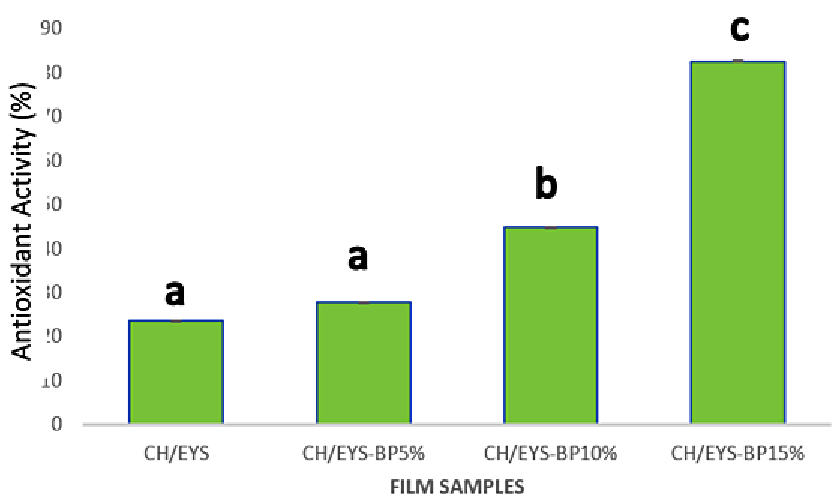

Figure 4. Antioxidant activity of CH/EYS-based bio-nanocomposite films with varying BP concentrations

The synergistic interaction between the chitosan/starch matrix and the BP extract likely stabilizes the anthocyanins, preserving their functionality within the bio-nanocomposite structure (Flores et al., 2022). This suggests that the films could be utilized in a variety of food packaging scenarios where antioxidant properties are crucial, such as for oil-based or perishable food items prone to oxidative spoilage.

X-ray diffraction

The X-ray diffraction (XRD) patterns of the bio-nanocomposite films composed of chitosan nanoparticles, elephant yam starch, and various concentrations of anthocyanin from butterfly pea extract (0%, 5%, 10%, and 15%) are shown in Figure 5. The control sample (0% anthocyanin) exhibits a broad peak around $2\theta = 20°$, which reflects the semi-crystalline nature of the biopolymeric matrix. This peak is typical for amorphous biopolymers such as starch and chitosan, indicating a predominantly amorphous structure, which enhances film flexibility and transparency. Upon the incorporation of 5% and 10% anthocyanin, the intensity of the diffraction peak at $2\theta = 20°$ increases slightly, with a slightly sharper profile observed at 10%. This trend suggests improved molecular alignment and a modest enhancement in crystallinity. Anthocyanin likely acts as a crosslinking agent, promoting better packing of polymer chains. This structural improvement is expected to contribute positively to mechanical properties, such as increased tensile strength, and reduced water vapor permeability (Hao et al., 2023). The addition of 10% anthocyanin appears to be particularly effective, further reinforcing the crystalline regions without causing significant disruption to the matrix.

However, with 15% anthocyanin, the intensity of the diffraction peak at $2\theta = 20°$ diminishes noticeably, and the peak profile broadens. This suggests that excessive anthocyanin disrupts the polymeric molecular arrangement, likely due to phase separation or aggregation of the anthocyanin molecules within the biopolymeric matrix (Erna et al., 2022). Such disruptions lead to a decline in crystallinity, which may negatively affect mechanical strength and thermal stability. On the other hand, increased amorphous regions could enhance functional properties such as antioxidant activity and biodegradability. This parallels findings in RGOC biocomposites, where excessive filler content caused reduced crystallinity by binding polymer chains and disrupting crystalline regions (Mindivan & Çolak, 2021). Such structural changes lead to a decline in mechanical and thermal stability but may enhance functional properties like antioxidant activity and biodegradability (Mindivan & Çolak, 2021) . Overall, the XRD results demonstrate that anthocyanin incorporation significantly influences the crystallinity of the films (Boonsiriwit et al., 2022). While 5–10% anthocyanin improves structural order, higher concentrations (15%) lead to a decrease in crystallinity. This highlights the importance of optimizing anthocyanin concentration to achieve

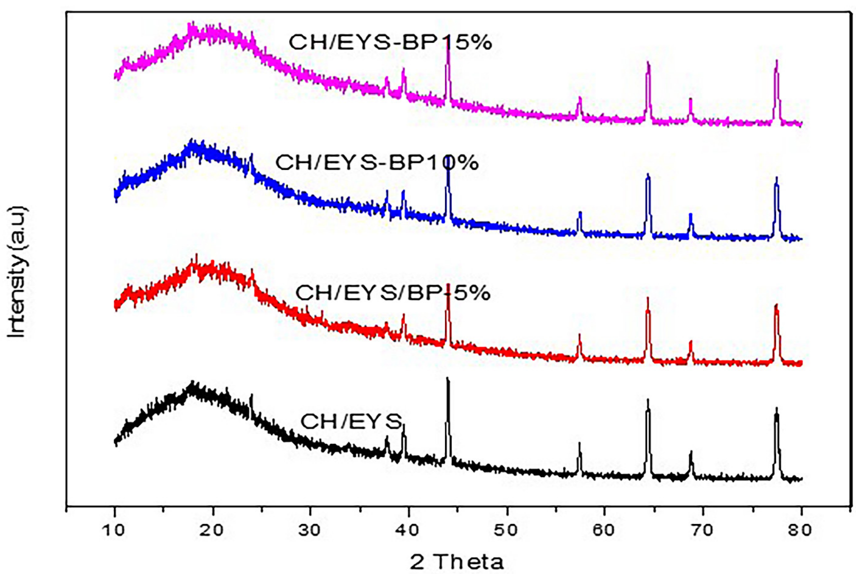

Figure 5. XRD diffractogram of CH/EYS bio-nanocomposite films at various BP content

a balance between functional and structural properties in the bio-nanocomposite films..

UV barrier

The UV-vis spectra of chitosan/elephant yam starch (CH/EYS) films containing butterfly pea (BP) anthocyanin at varying concentrations (0%, 5%, 10%, and 15%) are shown in the figure 6. These results provide insight into the UV-barrier properties of the films, which are critical for their potential application in food packaging to protect against UV-induced degradation (Dong et al., 2023). The pure CH/EYS film (0% BP) exhibits the lowest UV absorption across the UV region (200–400 nm), indicating limited UV-blocking capability. This is expected since neither chitosan nor elephant yam starch possesses strong chromophores capable of absorbing UV radiation effectively (Bof et al., 2021). The incorporation of BP anthocyanin significantly enhances the UV absorption of the films. At 5% BP, the UV absorption increases noticeably due to the presence of anthocyanins, which are known for their strong UV-absorbing properties. These natural pigments contain conjugated double-bond systems and aromatic rings that can absorb UV radiation effectively, thereby providing the film with a functional UV barrier (Hasan et al., 2024). With 10% BP anthocyanin, the UV absorption continues to increase, demonstrating a dose-dependent enhancement in UV-blocking performance. The higher anthocyanin content introduces more chromophoric groups into the film matrix, resulting in a more effective attenuation of UV radiation (Yun et al., 2019).

Interestingly, at 15% BP anthocyanin, the UV absorption remains comparable to that of the 10% BP sample, with only a slight improvement. This suggests that beyond 10%, the addition of anthocyanin reaches a saturation point, where further increments do not lead to significant increases in UV absorption. This behavior could be attributed to the aggregation of excess anthocyanin molecules within the matrix, which may hinder their uniform dispersion and reduce their overall effectiveness in enhancing UV absorption (Dong et al., 2023). Overall, the addition of BP anthocyanin imparts excellent UV-barrier properties to the CH/EYS films. The optimal concentration appears to lie between 5% and 10%, where a significant enhancement in UV absorption is achieved without aggregation effects. These findings highlight the potential of BP anthocyanin as a natural and sustainable UV-blocking additive for bio-based packaging materials.

CONCLUSIONS

The synthesis of bio-nanocomposite films from chitosan nanoparticles and elephant yam starch with varying concentrations of butterfly pea anthocyanin has demonstrated notable improvements in both structural and functional properties. FTIR analysis revealed significant changes in the hydrogen-bonding region, particularly with

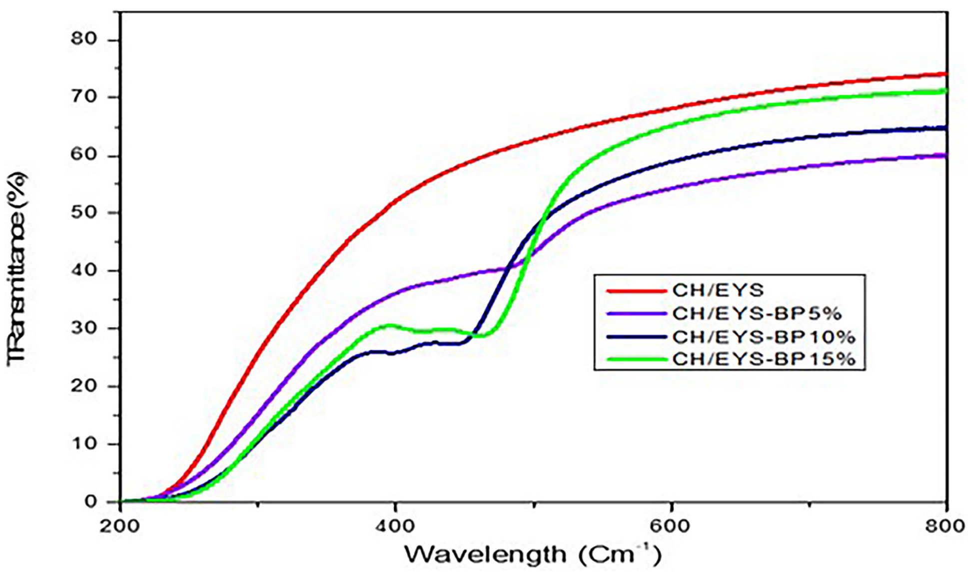

Figure 6. UV barrier performance of CH/EYS bio-nanocomposite film at various BP concentrations

increasing BP concentrations, suggesting enhanced interactions between the anthocyanins and the polymer matrix. DSC data indicated an increase in glass transition temperature (Tg) with higher BP content, reflecting stronger molecular interactions and reduced polymer chain mobility. Water vapor permeability and water uptake results showed a decrease in permeability with BP incorporation, particularly at the 10% concentration, enhancing the films' resistance to moisture transfer. Antioxidant activity increased with BP concentration, with the highest activity observed in films containing 15% BP, reaching an impressive 82.62%. XRD analysis revealed a slight increase in crystallinity, particularly at 10% BP, suggesting better polymer chain alignment and possible crosslinking by the anthocyanins. UV barrier performance also improved significantly with the addition of BP, with films containing 5% and 10% BP showing enhanced UV absorption due to the natural UV-blocking properties of anthocyanins. Overall, the incorporation of BP anthocyanins into the bio-nanocomposite matrix significantly improved the physical, chemical, and functional properties of the films, making them a promising material for various applications, including food packaging and UV protection.

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