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Development and Characterization of PLA/PBAT/Chitosan-Based Biodegradable Films for Active Strawberry Packaging Applications

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ABSTRACT

The increasing environmental concerns associated with conventional petroleum-based plastics have accelerated the development of sustainable and biodegradable packaging materials for food preservation applications. In this study, biodegradable films based on poly(lactic acid) (PLA), poly(butylene adipate-co-terephthalate) (PBAT), and chitosan were developed and evaluated as active packaging materials for extending the shelf life of strawberries. Six different film formulations were prepared, including neat PLA, PLA/chitosan, neat PBAT, PBAT/chitosan, PLA/PBAT blend, and PLA/PBAT/chitosan composite films. Chitosan was incorporated for its biodegradability, film-forming ability, UV-blocking properties, and antimicrobial properties, while PLA and PBAT were selected to combine the rigidity of PLA with the flexibility of PBAT. The structural, thermal, and optical properties of the prepared films were characterized using Fourier Transform Infrared Spectroscopy (FTIR), Thermogravimetric Analysis (TGA), and UV–Visible spectroscopy. FTIR analysis was employed to investigate intermolecular interactions among the polymeric components, whereas TGA was used to evaluate the thermal stability and degradation behavior of the films. UV–Vis measurements were conducted to determine the light barrier properties, which are critical for reducing photooxidative deterioration of fresh produce. The color and gloss properties of the obtained films were measured using an X-Rite eXact spectrophotometer. To evaluate the printability performance of the films, flexographic printing trials were conducted using an IGT F1 laboratory printing tester under controlled conditions. Following printing, the colorimetric and gloss characteristics of the printed films were re-evaluated to determine the influence of the film formulations on print quality. The practical applicability of the developed films was assessed through strawberry storage experiments. Changes in weight loss, visual appearance, color retention, firmness, and overall quality parameters were monitored during storage. It is anticipated that incorporating chitosan into PLA/PBAT-based systems will improve barrier properties and enhance strawberry preservation by reducing moisture loss and delaying spoilage. The findings of this study are expected to provide valuable insights into the design of environmentally friendly active packaging materials and demonstrate the potential of PLA/PBAT/chitosan composite films as sustainable alternatives to conventional food packaging systems.

KEY WORDS

Biodegradable packaging, chitosan, strawberry preservation, active food packaging

1. Introduction

The widespread use of conventional petroleum-based plastics has created serious environmental concerns, particularly because of their persistence in the environment and dependence on non-renewable fossil resources (Javed et al., 2026). The extensive use of plastics in food packaging has therefore increased the interest in sustainable and biodegradable alternatives. Although the primary function of food packaging is to protect food products from external factors and minimize quality losses during storage, current research has increasingly focused on active packaging systems that can provide additional protective functions (Hussain, Akhter & Maktedar, 2024). Incorporating properties such as antimicrobial activity, reduced ultraviolet (UV) transmission, and controlled moisture and gas transfer into packaging materials can be particularly beneficial for fresh fruits and vegetables with a short shelf life (Kontominas, 2026; Cazón, Mateus & Silva, 2025).

Poly(lactic acid) (PLA) is one of the most extensively studied biodegradable polymers for food packaging applications due to its potential production from renewable resources, biodegradability, good mechanical properties, transparency, and compatibility with conventional thermoplastic processing techniques (Hasoon & Panicker, 2026; Jayaseelan, 2024). Its relatively rigid structure and mechanical strength are advantageous for packaging applications.

However, its limited flexibility and relatively brittle nature can restrict its use in applications where greater toughness and deformability are required. The moisture barrier performance of PLA may also need further improvement depending on the intended application. For these reasons, considerable research has focused on blending PLA with other biodegradable polymers and incorporating functional components to tailor its properties for specific packaging requirements (Olonisakin et al., 2025; Ramli, 2026).

Poly(butylene adipate-co-terephthalate) (PBAT) is an aliphatic–aromatic copolyester that has attracted considerable attention as a flexible biodegradable polymer for packaging applications. Compared with PLA, PBAT generally exhibits higher flexibility, elongation at break, and toughness, which makes it suitable for packaging materials exposed to bending or mechanical deformation. On the other hand, its relatively low stiffness may limit its performance when used alone in applications requiring greater dimensional stability. Combining PLA and PBAT can therefore provide a practical approach for balancing the rigidity and mechanical strength of PLA with the flexibility and toughness of PBAT. The resulting properties of PLA/PBAT blends are strongly influenced by the composition, phase morphology, and interactions between the polymer components.

The incorporation of a natural functional component into such blends may provide an additional means of improving their performance and broadening their potential use in food packaging (Roy et al., 2024; Adeebpasha et al., 2026).

Chitosan is a natural polysaccharide mainly obtained through the deacetylation of chitin and has been widely investigated for food packaging because of its biodegradability, biocompatibility, film-forming ability, and inherent antimicrobial activity. The amino and hydroxyl groups present along its molecular structure can participate in interactions with other polymeric components, allowing the development of films with tailored properties. In particular, the antimicrobial activity of chitosan has made it an attractive component for packaging systems intended to slow microbial growth and extend the shelf life of fresh and processed foods.

Chitosan-containing films may also reduce light transmission and thus provide an additional protective function. However, the hydrophilic nature of chitosan can increase its sensitivity to moisture, which may affect the performance of the resulting films under humid conditions. Incorporating chitosan into more hydrophobic biodegradable polyester matrices such as PLA and PBAT may therefore offer a way to combine the functional characteristics of chitosan with the mechanical and processing advantages of biodegradable polyesters (Kartik, Shelly & Madurai, 2026).

Strawberries are among the fresh fruits that undergo rapid quality deterioration after harvest due to their high respiration rate, susceptibility to microbial growth, moisture loss, softening, and color changes. Their relatively short shelf life makes appropriate packaging particularly important during postharvest handling and storage (Aykanat et al., 2025). Moisture loss can lead to reductions in fruit weight and changes in texture, while microbial growth can accelerate spoilage. Exposure to oxygen and light may further contribute to oxidative deterioration and undesirable color changes. Consequently, packaging films designed for strawberry preservation should ideally provide more than mechanical protection. Control of moisture and gas transfer, reduced light transmission, and antimicrobial activity are desirable characteristics for maintaining strawberry quality during storage. Bringing these functions together in a biodegradable packaging material represents an important approach toward the development of active packaging systems for highly perishable produce (Lin & Jung, 2026).

In addition to food preservation performance, the optical and printing characteristics of packaging films are important from a practical and commercial perspective. Packaging materials not only protect food products but also serve as a surface for product identification, branding, and visual communication with consumers.

Film color, gloss, transparency, and printability can therefore influence the overall applicability of biodegradable packaging materials. Flexographic printing is widely used for flexible packaging because of its suitability for polymeric substrates and its potential for high-speed printing. However, differences in polymer composition and surface characteristics can influence ink transfer as well as the resulting color and gloss of printed films (Kumar et al., 2025). For this reason, evaluating the printing behavior of biodegradable films together with their structural, thermal, and optical properties can provide a more comprehensive assessment of their suitability for practical food packaging applications.

In the present study, six different biodegradable film formulations were developed with the aim of producing sustainable and active packaging materials for strawberry preservation. The formulations consisted of neat PLA, PLA/chitosan, neat PBAT, PBAT/chitosan, PLA/PBAT, and PLA/PBAT/chitosan films. The PLA/PBAT combinations were designed to obtain a more balanced combination of rigidity and flexibility, while the incorporation of chitosan was intended to introduce additional functional characteristics, particularly antimicrobial and light-barrier effects. The chemical structures of the films were investigated by Fourier Transform Infrared Spectroscopy (FTIR), while their thermal stability was evaluated using Thermogravimetric Analysis (TGA). UV–Visible spectroscopy was employed to assess their optical and light-barrier characteristics.

The color and gloss properties of the films were determined using an X-Rite eXact spectrophotometer, and their printability was examined through flexographic printing trials performed with an IGT F1 laboratory printing tester. The color and gloss properties were subsequently re-evaluated after printing to determine the effect of film composition on print quality. Finally, strawberry storage experiments were conducted to assess the practical performance of the developed films under food packaging conditions. Weight loss, visual appearance, color, firmness, and overall quality were monitored throughout storage. In this way, the study aimed to evaluate PLA-, PBAT-, and chitosan-based biodegradable films not only in terms of their material characteristics but also with respect to their printing performance and ability to maintain the quality of a real food product.

2. Methods

Polylactic acid (Mw ~60,000) used as a matrix was supplied from Sigma-Aldrich. Polybutylene adipate terephthalate and chitosan were purchased from Sigma-Aldrich. All solvents used in the experiments were of high purity and were obtained from Sigma Aldrich. Strawberries were obtained from the local agricultural center in Türkiye.

2.1. The preparation of the active packaging films

PLA, PBAT, and PLA/PBAT-based packaging films with and without chitosan were prepared by the solvent casting method. Prior to film preparation, PLA and PBAT pellets were dried under vacuum at 80 °C for 8 h to remove residual moisture.

Six different film formulations were prepared: neat PLA, PLA/chitosan, neat PBAT, PBAT/chitosan, PLA/PBAT, and PLA/PBAT/chitosan.

For the preparation of the PLA films, PLA pellets were dissolved in chloroform under continuous stirring at room temperature until a homogeneous polymer solution was obtained. For the PLA/chitosan formulation, a predetermined amount of chitosan powder was directly added to the PLA solution without prior dissolution.

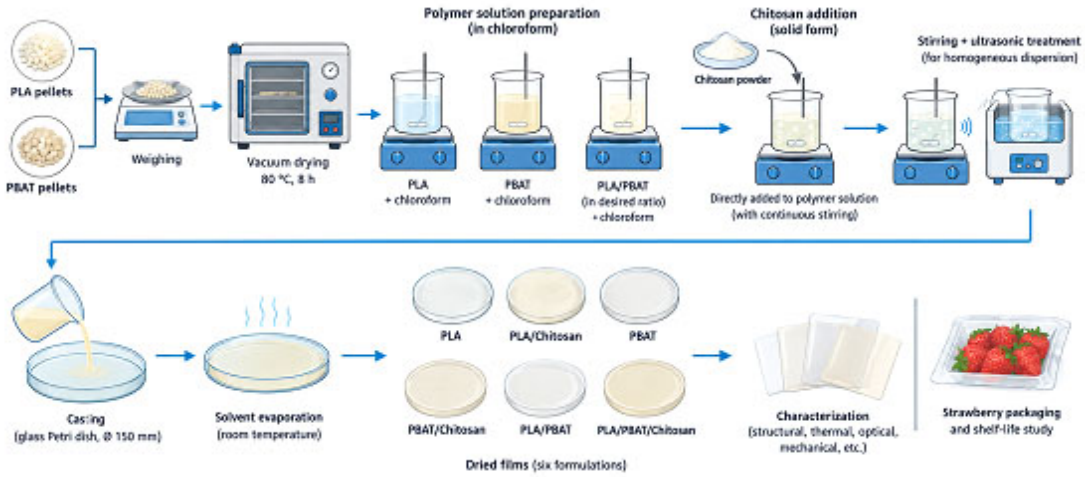
The mixture was continuously stirred to promote the homogeneous dispersion of chitosan within the polymer solution. Similarly, PBAT films were prepared by dissolving PBAT in chloroform, while the PBAT/chitosan formulation was obtained by directly incorporating chitosan powder into the PBAT solution under continuous stirring.

For the PLA/PBAT blend films, predetermined amounts of PLA and PBAT were dissolved in chloroform and mixed thoroughly to obtain a homogeneous polymer blend. For the PLA/PBAT/chitosan formulation, chitosan powder was directly added to the PLA/PBAT solution and dispersed under continuous stirring. In all chitosan-containing formulations, chitosan was incorporated in its solid form and was not subjected to a separate dissolution step.

The resulting film-forming formulations were subjected to ultrasonic treatment to improve the dispersion of chitosan and reduce the formation of visible aggregates.

Subsequently, the formulations were cast onto glass Petri dishes (diameter: 150 mm) and allowed to dry under room conditions until complete solvent evaporation. The dried films were carefully removed from the Petri dishes and stored in a desiccator until further characterization and packaging experiments.

The films were coded according to their compositions as PLA, PLA/Chitosan, PBAT, PBAT/Chitosan, PLA/PBAT, and PLA/PBAT/Chitosan. The neat PLA and PBAT films and the PLA/PBAT blend were used as reference formulations, while the corresponding chitosan-containing films were prepared to investigate the effect of chitosan incorporation on the physicochemical, thermal, optical, and packaging properties of the films. A schematic representation of the film preparation procedure is presented in Figure 1.



» **Figure 1:** *A schematic representation of the film preparation procedure*

2.2. Characterization

Fourier-Transform Infrared Spectroscopy (FTIR) analysis was conducted using a Bruker IFS 66/S spectrometer equipped with ATR capability. Thermal gravimetric analysis (TGA) was performed with a Perkin Elmer STA6000 instrument, with measurements carried out in the temperature range of 30°C to 750°C under a nitrogen atmosphere at a heating rate of 10°C/min. The colors of the obtained nanocomposite packaging films were measured by X-Rite eXact portable spectrophotometer according to the ISO 13655:2017 standard. The measurement conditions of the spectrophotometer were determined as a polarization filter with 0/45° geometry with a 2° observer angle and a D50 light source in the range of 400-700 nm. Color differences were calculated using the CIELab (2000) technique (Equation 1). ISO 11664-6:2014.

Calculations were performed by calculating the average of five measurements. ΔL*, Δa*, and Δb*: Difference in L*, a*, and b* values between the specimen and target colors, respectively. The lightness is represented by the L* axis, which ranges from white to black. The red area is connected to green by the a* axis, whereas the b* axis runs from yellow to blue. (1) Where ΔL*, ΔC*, and ΔH* are the CIEL*a*b* metric lightness, chroma, and hue differences, respectively, calculated between the standard and sample in a pair, and ΔR is the interaction term between the chroma and hue differences. SL, SC, and SH are the weighting functions for lightness, chroma, and hue components. The values calculated for these functions vary according to the positions of the sample pair considered in the CIEL*a*b* color space. The kL, kC, and kH values are the parametric factors to be adjusted according to different viewing parameters, such as textures, backgrounds, and separations, for the lightness, chroma, and hue components. The gloss measurements of all nanocomposite packaging films were carried out with the BYK Gardner GmbH micro gloss 75° geometry by ISO 8254-1:2009.

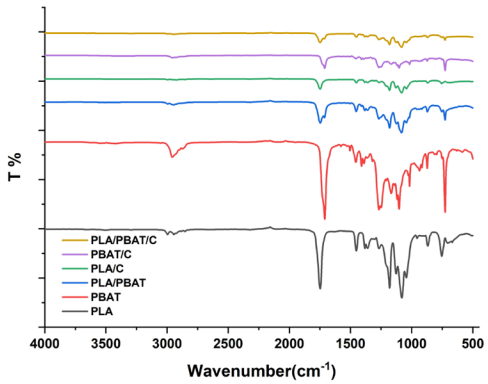
The contact angles of nanocomposite packaging films were found on Pocket Goniometer Model PG-X, version 3.4 (FIBRO Systems AB, Sweden). Surface-free energy was calculated according to the ASTM D5946 standard test method, depending on the water contact angle. The images of droplets were then recorded by using a CCD video camera. The transparency of the nanocomposite packaging films was examined visually. Gravure prints were made on the obtained films with SEIGWERK ethyl alcohol solvent blue 20 seconds viscosity ink at 1m/s printing speed with RK printing proofer, and the color properties of the obtained prints were determined by X-Rite eXact portable spectrophotometer according to the ISO 13655:2017 standard. To examine the storage of fresh strawberry using nanocomposite packaging films, strawberry were obtained from the local agricultural center in Türkiye. Fresh strawberry were characterized by a red color (80 % ripening stage), where unblemished, rot-free, well-formed strawberry were selected. Three selected strawberries of the same maturity were placed in the middle of the dried nanocomposite packaging film with three different contents. The strawberries were tightly wrapped with nanocomposite packaging films. All specimens were stored at room temperature and the same relative humidity and were examined both visually and tactilely daily.

3. Results

3.1. Structural characterization of the packaging films

FTIR spectroscopy was used to investigate the chemical structures and possible molecular interactions among PLA, PBAT, and chitosan in the biodegradable packaging films. Figure 2 presents the FTIR spectra of neat PLA, PLA/chitosan, neat PBAT, PBAT/chitosan, PLA/PBAT, and PLA/PBAT/chitosan films.

The characteristic absorption bands of the individual polymers were observed in the spectra of the corresponding films, confirming the presence of their main functional groups.



» **Figure 2:** *FTIR spectra of neat PLA, PLA/chitosan, neat PBAT, PBAT/chitosan, PLA/PBAT, and PLA/PBAT/chitosan films*

The FTIR spectrum of the neat PLA film showed the characteristic absorption bands associated with its ester groups and aliphatic carbon chains. The bands observed in the region of approximately 2995–2945 cm^{-1} can be assigned to the asymmetric and symmetric stretching vibrations of C–H groups, respectively. The strong absorption band around 1750–1760 cm^{-1} corresponds to the stretching vibration of the ester carbonyl (C=O) groups, which is characteristic of PLA.

The absorption bands observed in the region of approximately 1450–1360 cm^{-1} can be attributed mainly to C–H bending vibrations. In addition, the bands in the range of approximately 1300–1000 cm^{-1} are associated with C–O and C–O–C stretching vibrations of the ester groups in the PLA backbone. These characteristic bands confirm the polyester structure of the PLA film (Alpdoğan et al., 2025).

The spectrum of the neat PBAT film exhibited the characteristic absorption bands associated with its aliphatic and aromatic ester structure. The strong band observed around 1710–1720 cm^{-1} can be attributed to the stretching vibration of the ester carbonyl (C=O) groups. The bands in the region of approximately 2950–2850 cm^{-1} are related to the C–H stretching vibrations of the aliphatic segments. The absorption bands observed in the lower wavenumber region, particularly between approximately 1300 and 1000 cm^{-1}, can be associated with C–O and C–O–C stretching vibrations of the ester groups. In addition, bands related to the aromatic terephthalate units can be observed in the region of approximately 1600–1450 cm^{-1}. The presence of these characteristic absorptions is consistent with the chemical structure of PBAT.

The incorporation of chitosan resulted in additional absorption bands associated with its polysaccharide structure. In the FTIR spectra of the PLA/chitosan, PBAT/chitosan, and PLA/PBAT/chitosan films, the broad band appearing in the region of approximately 3200–3500 cm^{-1} can be assigned to the overlapping O–H and N–H stretching vibrations of chitosan. The bands around 2920–2870 cm^{-1} are associated with C–H stretching vibrations. The characteristic absorption bands of chitosan in the region of approximately 1650–1550 cm^{-1} can be related to the amide I and amide II groups, respectively. Furthermore, the absorption bands observed in the region of approximately 1150–1000 cm^{-1} are mainly associated with C–O–C and C–O stretching vibrations of the polysaccharide backbone. The appearance or increased intensity of these bands in the chitosan-containing films provides evidence for the incorporation of chitosan into the polymeric film matrix.

For the PLA/chitosan films, the characteristic carbonyl band of PLA remained clearly visible, while the broad O–H/N–H absorption associated with chitosan became more pronounced compared with the neat PLA film. Any changes in the position, width, or intensity of these bands may indicate interactions between the hydroxyl and amino groups of chitosan and the ester groups of PLA. Such interactions can occur through hydrogen bonding between the polar functional groups of the two components. However, the absence of a new, distinct absorption band suggests that the incorporation of chitosan does not result in the formation of a completely new chemical structure, but rather promotes intermolecular interactions within the composite film.

A similar behavior was observed for the PBAT/chitosan films. The characteristic carbonyl absorption of PBAT remained detectable after the addition of chitosan, while the broad O–H/N–H stretching region became more prominent. The coexistence of the characteristic bands of PBAT and chitosan indicates that both components were retained in the resulting film structure. Changes in the intensity and/or position of the carbonyl and hydroxyl/amino-related bands can be associated with intermolecular interactions between the polyester matrix and chitosan. These interactions may influence the morphology, mechanical behavior, and barrier characteristics of the resulting films (Alpdoğan et al., 2025).

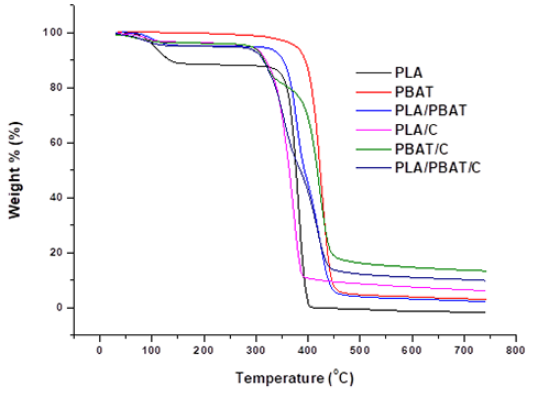
The FTIR spectrum of the PLA/PBAT blend film contained the characteristic absorption bands of both polyesters. In particular, the strong carbonyl absorption associated with the ester groups and the bands attributed to C–H and C–O–C stretching vibrations were maintained after blending. The presence of the characteristic bands of both polymers without the appearance of an entirely new dominant absorption band suggests that the blending process primarily resulted in physical mixing and intermolecular interactions rather than

the formation of new covalent bonds. Nevertheless, changes in peak intensity, broadening, or slight shifts in the characteristic bands may reflect interactions between the PLA and PBAT chains and changes in the local chemical environment within the blend.

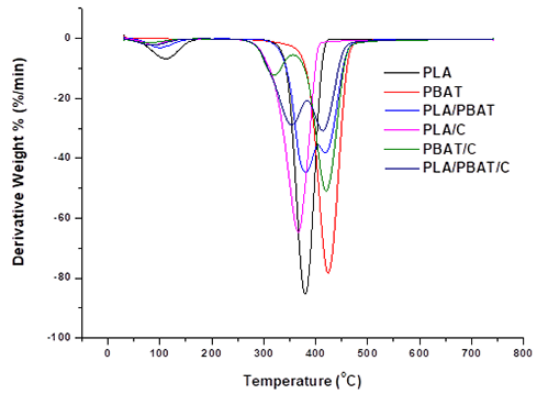
The PLA/PBAT/chitosan film exhibited the characteristic absorption bands of all three components. The ester carbonyl and C–O–C bands originating from PLA and PBAT were observed together with the broad O–H/N–H stretching band and other characteristic absorptions associated with chitosan.

The simultaneous presence of these bands confirms the successful incorporation of PLA, PBAT, and chitosan into the composite film. Compared with the corresponding binary systems, changes in the relative intensity and position of some characteristic bands may indicate increased intermolecular interactions among the three components.

In particular, hydrogen bonding involving the hydroxyl and amino groups of chitosan and the carbonyl groups of PLA and PBAT may contribute to the observed spectral changes.



(a)



(b)

» **Figure 3:** *a) TGA curves of the packaging films, b) DTG curves of the packaging films*

3.2. Thermal characterization of the packaging films

Figure 3 presents the TGA curves of the biodegradable packaging films, while the corresponding thermal analysis results are given in Table 1. All films exhibited a distinct mass loss with increasing temperature, and their thermal degradation behavior varied depending on the film composition.

The main degradation observed for the neat PLA and PBAT films can be attributed to the decomposition of the polyester chains and ester groups. For the PLA/chitosan and PBAT/chitosan films, the degradation of the polysaccharide structure of chitosan occurred together with the degradation of the polyester component. This resulted in changes in the TGA profiles and maximum degradation temperatures of the chitosan-containing films.

The thermal behavior of the PLA/PBAT film reflects the combined degradation characteristics of both polyesters, whereas the PLA/PBAT/chitosan film is influenced by the contribution of all three components. Possible hydrogen bonding between the hydroxyl and amino groups of chitosan and the carbonyl groups of the polyesters may affect the intermolecular interactions within the films and, consequently, their thermal degradation behavior.

The higher residue content at elevated temperatures observed for the chitosan-containing films can be associated with the carbonization tendency of the chitosan structure. Overall, the TGA results indicate that the film formulation has a significant effect on both the thermal degradation temperature and the residual mass at high temperatures (Alpdoğan et al., 2025).

Table 1

TGA results of the packaging films

Formulations	T_5 (°C)	T_{max} (°C)	Char %
PLA	109.71	381.64	0
PBAT	376.65	426.07	3.1
PLA/PBAT	133.99	376.69	2.1
PLA/C	234.42	371.35	6.1
PBAT/C	292.76	423.33	11
PLA/PBAT/C	148.9	348.39	10

3.3. Color properties of the packaging film

The initial visual appearance and post-printing CIE L* a* b* color coordinates of the developed films are presented in Table 2. The neat PLA and PBAT films were visually transparent, whereas the PLA/PBAT film exhibited a white appearance. The incorporation of chitosan changed the visual appearance of the films to a yellowish-white color.

This change indicates that chitosan addition affected the optical characteristics of the polymer matrices and is consistent with the ability of chitosan-containing systems to modify the surface and bulk properties of PLA-based materials (Aydemir, Altay & Akyol, 2021; Gartner, Li & Almenar, 2015).

A particularly important observation was obtained for the chitosan-containing films. Although PLA/chitosan, PBAT/chitosan and PLA/PBAT/chitosan films exhibited a similar yellowish-white appearance before printing, they did not show the same printing behaviour. While PBAT/chitosan could be successfully printed, effective ink transfer was not achieved on PLA/chitosan and PLA/PBAT/chitosan under the applied printing conditions. This finding indicates that the poor printability observed in the latter films cannot be attributed solely to the presence of chitosan. Rather, the effect of chitosan appears to be dependent on the polymer matrix (Izdebska-Podsiadły, 2021).

Ink transfer and adhesion on polymeric substrates are strongly governed by surface chemistry, wettability, surface energy and the compatibility between the ink and substrate. Aydemir, Altay and Akyol (2021) reported that the interaction between inks and polymer substrates is determined by the balance between polar and dispersive interactions, and that compatibility between the surface characteristics of the substrate and the ink is essential for effective wetting and adhesion. Similarly, previous research on flexographic printing of compostable PLA/PBAT films demonstrated that these films may exhibit limitations in ink adhesion, highlighting the importance of substrate surface characteristics in printability (Hansuebsai & Nawakitwong, 2020).

The different behaviors observed among the chitosan-containing films may therefore be related to changes in the surface characteristics generated by the interaction between chitosan and the polyester matrix. Chitosan contains hydroxyl and amino functional groups and can modify the wettability and interfacial characteristics of PLA-based systems. Gartner, Li and Almenar (2015) demonstrated that the incorporation of chitosan into PLA-based structures can substantially affect wettability and interfacial adhesion, while changes in intermolecular interactions can further modify the adhesion behavior. Thus, the presence and distribution of chitosan at the film surface may alter the interaction between the substrate and the solvent-based printing ink.

The successful printing of PBAT/chitosan, despite its yellowish-white initial appearance, is particularly significant. It demonstrates that the initial color of the substrate and the presence of chitosan alone are not sufficient to predict printability. Instead, the final printing response appears to depend on the specific surface characteristics generated by the interaction between the polyester matrix and chitosan.

This matrix-dependent behavior is also consistent with previous studies showing that changes in the surface properties of biodegradable polymer films can significantly influence ink wetting, ink-layer formation and print quality (Aydemir, Altay & Akyol, 2021; Izdebska-Podsiadły, 2021).

Table 2

Visual appearance and CIELAB color coordinates of the films after printing

Film sample	Initial visual appearance	L*	a*	b*	Printing result
PLA	Transparent	17	19	–53	Successful ink transfer
PBAT	Transparent	14	16	–47	Successful ink transfer
PLA/PBAT	White	17	14	–47	Successful ink transfer
PLA/Chitosan	Yellowish-white	78	–1	+10	No effective ink transfer
PBAT/Chitosan	Yellowish-white	27	5	–53	Successful ink transfer
PLA/PBAT/Chitosan	Yellowish-white	80	–2	+8	No effective ink transfer

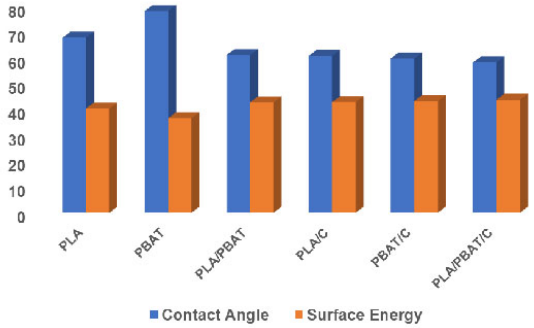
Overall, the colorimetric results clearly distinguish between successful and unsuccessful ink transfer. Successfully printed films exhibited a pronounced color shift towards the blue region, whereas PLA/chitosan and PLA/PBAT/chitosan retained their initial yellowish-white appearance.

These findings demonstrate that CIELAB measurements can provide objective support for the visual assessment of print transfer. More importantly, the contrasting behavior of PBAT/chitosan and PLA/chitosan-based films indicates that the effect of chitosan on printability is matrix-dependent rather than simply related to its presence in the formulation. Therefore, optimization of biodegradable polyester/chitosan films for printing applications should consider not only the bulk formulation but also the surface chemistry, wettability and ink–substrate compatibility.

3.4. Surface properties of the packaging film

The contact angles and surface energy values of the prepared packaging films were investigated, and the results are presented in Figure 4. The contact angle of the neat PBAT film was measured as 78.4°, indicating a relatively hydrophobic surface. In comparison, the neat PLA film exhibited a lower contact angle of 68.0°. The lower contact angle of PLA suggests a relatively higher surface polarity, which is also consistent with its higher surface energy (40.5 mN/m) compared with PBAT (36.7 mN/m).

The incorporation of chitosan resulted in a noticeable decrease in the contact angle of both PLA and PBAT films. The contact angle decreased from 68.0° for neat PLA to 61.0° for PLA/chitosan, while the corresponding surface energy increased from 40.5 to 43.0 mN/m. Similarly, the contact angle of PBAT decreased from 78.4° to 60.0° after the incorporation of chitosan, accompanied by an increase in surface energy from 36.7 to 43.4 mN/m. This behavior can be attributed to the hydrophilic hydroxyl and amino groups present in the chitosan structure, which increase the polarity of the film surface and promote stronger interactions with water.

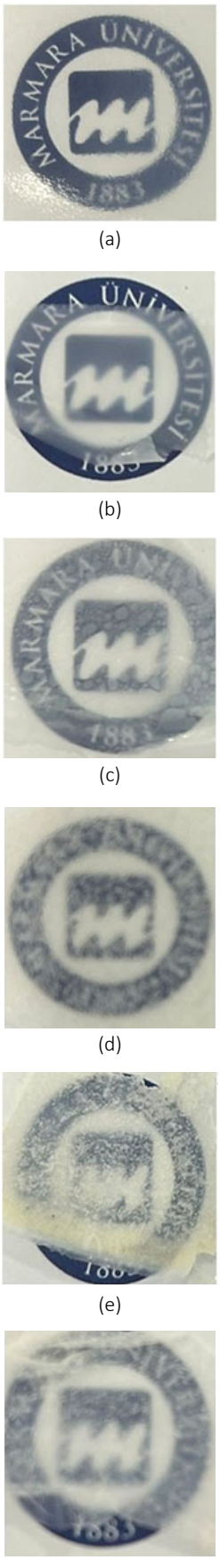


» **Figure 4:** *Contact angles and surface energies of the nanocomposite packaging films*

The PLA/PBAT blend exhibited a contact angle of 61.3° and a surface energy of 42.9 mN/m, indicating that blending the two polyesters substantially increased the surface polarity compared with neat PBAT. The lowest contact angle was observed for the PLA/PBAT/chitosan film (58.4°), which also showed the highest surface energy (43.9 mN/m).

This result indicates that the combined presence of PLA, PBAT, and chitosan produced the most hydrophilic surface among the investigated films. Overall, the decrease in contact angle and the corresponding increase in surface energy following chitosan incorporation suggest that chitosan plays an important role in modifying the surface characteristics of the packaging films. These changes may also influence the wettability, adhesion, and printability of the films, which are important properties for packaging applications.

As illustrated in Figure 5, flexible and translucent packaging films were successfully prepared by the solvent casting method. Among the investigated films, neat PLA exhibited the highest transparency, followed by PBAT and PLA/PBAT films. The relatively high transparency of PLA can be associated with its homogeneous film structure and good optical uniformity. PBAT also showed a relatively transparent appearance, whereas the PLA/PBAT blend exhibited a moderate decrease in transparency, which may be related to differences in the optical properties and phase structure of the two polymers.



» **Figure 5:** *Images of a) PLA, b) PBAT, c) PLA/PBAT, d) PLA/C, e) PBAT/C, and f) PLA/PBAT/C packaging films*

The incorporation of chitosan resulted in a noticeable decrease in the transparency of the films. This effect was observed for both the individual polymers and the PLA/PBAT blend. The reduction in transparency may be attributed to the heterogeneous distribution of chitosan within the polymer matrix and the resulting increase in light scattering at the polymer–chitosan interfaces. In addition, possible intermolecular interactions between chitosan and the polyester matrices may affect the microstructure of the films and contribute to their opaquer appearance. Overall, the results indicate that the optical properties of the prepared films are strongly influenced by both polymer composition and chitosan incorporation, with neat PLA providing the most transparent film among the formulations investigated.

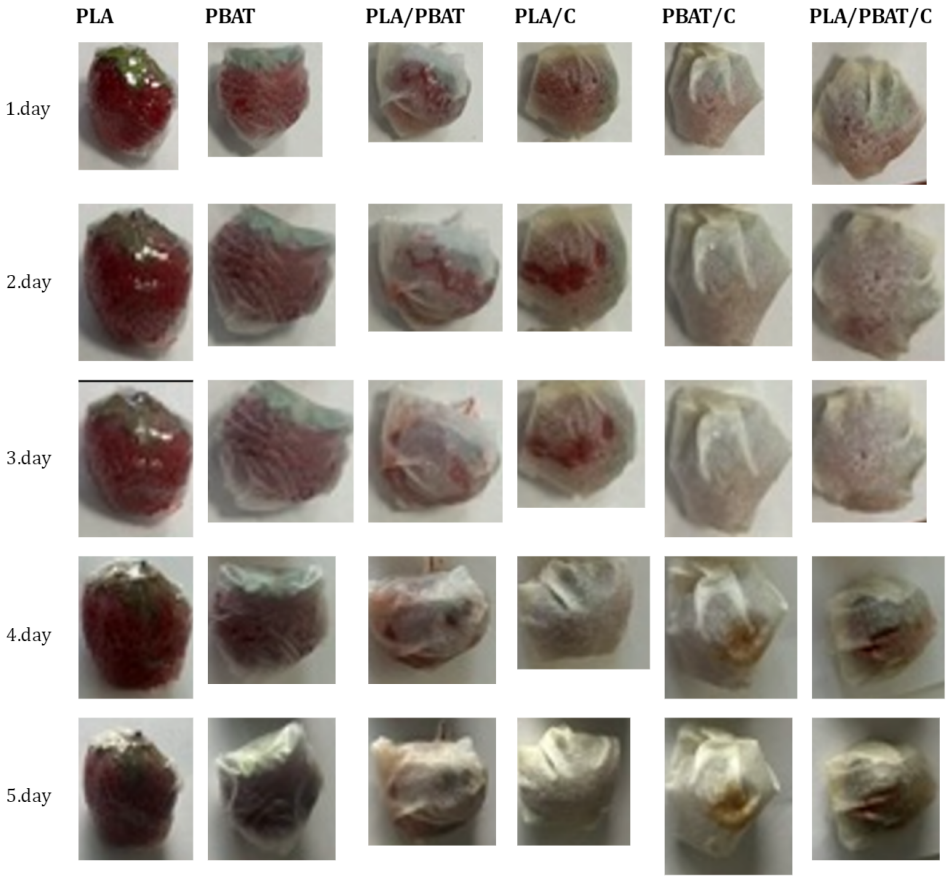
Strawberries are highly perishable fruits with a short postharvest shelf life due to their high moisture content, respiration rate, and susceptibility to microbial deterioration. Therefore, the effect of the prepared packaging films on the preservation of fresh strawberries was evaluated during storage by monitoring changes in their visual appearance, color, weight loss, and overall quality. Figure 6 presents photographs of the strawberries packaged with the prepared films during the storage period. Noticeable differences in the appearance of the strawberries were observed depending on the film composition.

3.5. Storage studies of the nanocomposite packaging film

The strawberries packaged with neat PLA, PBAT, and PLA/PBAT films showed changes in appearance during storage, while the incorporation of chitosan generally helped maintain a better visual appearance.

In particular, the PLA/PBAT/chitosan film provided a more favorable preservation effect, with the strawberries maintaining their fresh appearance for a longer period compared with those packaged with the corresponding polyester films without chitosan. The improved preservation performance of the chitosan-containing films may be associated with the antimicrobial properties of chitosan and its contribution to the barrier characteristics of the packaging system. In addition, the combination of PLA and PBAT may provide a more balanced film structure by combining the rigidity of PLA with the flexibility of PBAT.

Overall, the photographic observations indicate that film composition plays an important role in maintaining strawberry quality during storage. Among the formulations investigated, the PLA/PBAT/chitosan film showed promising potential for extending the visual quality and freshness of strawberries, suggesting that the combination of PLA, PBAT, and chitosan can be advantageous for biodegradable active food packaging applications.



» **Figure 6:** *Photographs of the strawberries packaged with the prepared films during the storage period*

4. Conclusions

In this study, biodegradable PLA, PBAT, and PLA/PBAT-based packaging films containing chitosan were developed by the solvent casting method and evaluated as potential packaging materials for fresh strawberries. The effects of polymer composition and chitosan incorporation on the structural, thermal, surface, optical, and printing properties of the films were investigated, together with their performance during strawberry storage.

The FTIR results confirmed the characteristic functional groups of PLA, PBAT, and chitosan in the corresponding films, while the observed spectral changes suggested intermolecular interactions between the film components. TGA analysis showed that the thermal degradation behavior of the films was affected by their composition, with chitosan incorporation contributing to changes in the degradation profiles and residual mass. Surface characterization revealed that the incorporation of chitosan decreased the contact angle and increased the surface energy of both PLA- and PBAT-based films, indicating an increase in surface polarity. Among the prepared films, neat PLA exhibited the highest transparency, followed by PBAT and PLA/PBAT, whereas the addition of chitosan reduced the transparency of the films.

The prepared films also showed suitable characteristics for printing applications, while their optical and surface properties were influenced by the polymer composition and the presence of chitosan. During strawberry storage, the chitosan-containing films generally provided better preservation of the visual appearance and freshness of the fruit. In particular, the PLA/PBAT/chitosan film showed promising performance in maintaining strawberry quality compared with the corresponding films without chitosan. This behavior can be associated with the antimicrobial character of chitosan and the complementary properties of PLA and PBAT.

Overall, the results demonstrate that the combination of PLA, PBAT, and chitosan can provide biodegradable packaging films with tunable surface, optical, thermal, and functional properties. Among the formulations investigated, PLA/PBAT/chitosan showed considerable potential for fresh strawberry packaging and may represent a promising alternative to conventional petroleum-based packaging materials.

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