Polymer Bulletin (2026) 83:394
https://doi.org/10.1007/s00289-026-06466-7

ORIGINAL PAPER

Incorporating lignin into chitosan-based bioplastics enhances the tensile properties and provides control of swelling and opacity

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Received: 14 March 2025 / Revised: 13 April 2026 / Accepted: 27 April 2026 /
Published online: 5 May 2026
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Abstract

This study focuses on obtaining and characterizing bioplastics prepared with different mass amounts of commercial chitosan and lignin extracted from guava seed cake. The chitosan-lignin bioplastics were produced using the casting technique, and characterized through thermogravimetric analysis, tensile tests, swelling (water absorption), water solubility, and moisture. All bioplastics containing lignin exhibited moisture percentages higher than the only-chitosan sample (15.7%); the formulation with the lignin maximum content (10%) reached the highest content (19.4%). Water solubility did not show significant statistical differences; the average value was 17.4%. The increasing lignin content revealed a strong positive linear correlation ($R = 0.95$) with opacity, with the maximum one (4.92 mm^{-1}) found in the formulation with the highest lignin content. Conversely, the increasing lignin content revealed an inverse linear correlation ($R = 0.83$) with swelling, reducing it from 276.6% (only chitosan formulation) to 133.5% (formulation with the highest lignin content). The tensile strength of formulations containing lignin was higher than that of the only-chitosan specimen (12.5 MPa). However, the breaking elongation of formulations with lignin (except the formulation with 2% lignin content) was lower than that of the only-chitosan bioplastic (36.6%). According to thermogravimetric analysis, all samples had their mass losses in four distinct steps, the lignin incorporation raised the temperature at which the bioplastics showed their maximum mass losses, and the lowest mass loss rate was observed in the formulation with the highest lignin content. The cryofracture cross-section image for the formulation with the highest lignin content did not exhibit layer formation, therefore the chitosan-lignin in the study condition can originate blends.

Keywords Biomass · Natural polymers · Biopolymer · Bio-based films · Agroindustrial waste

Extended author information available on the last page of the article

Introduction

Of the worldwide production of plastics projected for 2030, only 0.5% (almost 3 million tons) will correspond to bioplastics, which is expected to have a production growth of 29.3% for the period 2020–2030 [1]. Although plastics have brought benefits to societies, they are responsible for several problems, such as greenhouse emissions (from exploration and refining processes, and use of derivatives), coming from non-renewable sources (oil), low recycling and reuse rates, contamination of water and soil (by direct or landfill disposal), air pollution (by open burning), very slow biodegradation, and vast production and buildup of wastes [2–5]. To beat these issues, replacing plastics with bioplastics is highly desirable for current and future applications, such as food packaging [6]. Bioplastics come from natural polymers that are, in turn, in the biomass internal structure. Biomass is an accessible, renewable, and plentiful raw material, and if its origin is from wastes, then it will not compete with the biomass intended for food [5, 7, 8]. Starch, lignin (LG), hemicelluloses, cellulose, pectin, and chitin are natural polymers that are extracted from biomass wastes and are used for bioplastic obtaining [9].

Although starch is the most frequently employed natural polymer to produce bioplastics, other raw materials such as LG and chitosan (Ch) have the potential to be promising precursors [10–12]. LG is the second most abundant natural polymer on earth, its composition is based on three basic precursor units (coniferyl, sinapyl, and p-coumaryl alcohol), and has a three-dimensional, heterogeneous, and highly irregular (cross-linked and branched) structure [13]. In plants, LG acts as a shield from environmental threats and provides structural strength, which is an important property to be explored in the development of biopolymers [14, 15]. However, the LG structure varies according to the type of biomass source, and to the process used for its extraction [13].

Although Ch comes from chitin, it is also considered a natural polymer that technically is produced in industries through the chemical deacetylation of chitin, which in turn is extracted from seafood industrial wastes (mainly crustacean shells) [16]. Ch of high purity (which indicates a high abundance of glucosamine chains) is molecularly similar to cellulose due to the presence of the same β-glycoside bonds, however, high-purity Ch has amino groups located where cellulose has its hydroxyl groups [17]. Ch purity is usually determined with the deacetylation degree test, which measures the presence of glucosamine monomers; a high deacetylation degree indicates a high content of glucosamine units, whereas a low deacetylation degree indicates a high content of N-acetyl-glucosamine units [18]. Due to its biocompatibility, biodegradation, antimicrobial properties, and processing simplicity, Ch is a promising raw material for replacing common plastics [11]. In recent research, bioproducts based on Ch, such as gels in tissue engineering, microcapsules for medicine release, and films for packaging have been developed [11, 19]. Nevertheless, when gels and films are made of only Ch, these are translucid and fragile (low strength and toughness), which hinders their use as light-protective and load-bearing materials [6, 20].

Despite previous research about the production of bioplastics containing Ch and LG (as an additive) resulted in materials with different properties, further research is necessary, mainly because LG structure depends on the biomass type and on its

extraction process (as mentioned above). Luo et al. (2023) [6] and Jaganathan et al. (2018) [21] reported that LG incorporation in Ch-based bioplastics improved tensile properties. Thus, the present research aimed to manufacture and evaluate films using Ch (commercial) and LG extracted from the spent liquor generated after alkali ethanolic organosolv pretreatment of guava seed cake. This industrial waste corresponds to the press cake that originated after the oil extraction process from the guava seed. Although the mass balance of guava seed cake production is unknown, some information is available that can help infer its availability. In 2022, the worldwide production of guava achieved 40 million tons, and it is estimated that during its processing, nearly 30% (of the fresh fruit) is considered residue (seeds, rinds, and pulp). This one contains around 13% of oil, which is industrially extracted, generating the seed cake [22]. Some recent research pointed out the guava seed cake as a raw material with high potential for obtaining bioproducts due to its lignocellulosic composition [23]. However, for lignocellulosic biomass harnessing, its chemical structure needs to be modified through a pretreatment stage. Among pretreatments, the ethanolic organosolv process catalyzed by alkali is one of the most useful for valorization of lignocellulosic wastes, because the internal chemical compounds are selectively fractionated by the solvent and catalyst actions, which break hydrogen, ether and glycoside bonds present in the lignocellulosic structure [24].

The present research aimed to produce and evaluate bioplastic using Ch (commercial) and LG extracted from the spent liquor generated after alkali ethanolic organosolv pretreatment of guava seed cake. The characterization of the produced bioplastic was performed by thermal stability and a thermogravimetric analysis (TGA). To define the mechanical integrity were used tensile tests (tensile strength, breaking elongation, and Young´s modulus). Moisture and water solubility percentages were calculated to indicate the water interaction, and opacity determination contributed to evaluate the light control of the produced polymeric films. The swelling was measured by the dimensional change in water, which, along with water solubility, is vital for food packaging applications aiming to prevent moisture migration and ensure product integrity [25, 26].

Experimental

Materials

The Condire industry settled in Dois Córregos, São Paulo state, Brazil (−22º 22’ 6.9’’ N −48º 23’ 51.01’’W), which kindly provided the guava seed cake (dried). After the size reduction step, the waste reached an average dimension below 0.841 mm (mesh 20) [27]. The waste was dried for 24 h at 50 °C, and stored in a plastic bottle. The Ch used in the present study was of commercial type (C3646 of Sigma-Aldrich, source: shrimp shells - SLCK9065, and PCode: 1003345975), and its deacetylation degree was 81.2 ± 0.65% (determined by potentiometric method) and 80.6 ± 0.08% (by Fourier Transform Infrared spectroscopy). Sodium hydroxide p.a., calcium nitrate tetrahydrate p.a., and 99.8% glacial acetic acid p.a. were acquired from Neon Comercial. And, 92.8% ethanol from Safra Industria and glycerin P.A. from Labsynth®.

Extraction of lignin (LG)

In a stainless-steel reactor (with a nominal capacity of 75 mL) was put the guava seed cake, NaOH, and a 70% (m/m) ethanolic aqueous solution; the waste: alkali: solution ratio was maintained at 10:6:50. After mixing the system with a glass rod and soaking for 45 min, the pretreatment took place at 170 °C in an oil bath for 1 h. After the reaction, the spent liquor was recovered using filter paper, and the hemicelluloses were removed. The removal process occurred by precipitation and involved two successive stages: addition of 92.8% ethanol to the spent liquor, followed by decantation for 18–20 h [28]. After the precipitation of hemicelluloses, the filtrate was collected [29] and boiled at 80 °C to evaporate the added ethanol, and sulfuric acid was poured into the concentrated solution until the pH was below 2. Then, the suspension completed a resting period of 18–20 h. Finally, LG was recovered by filtration, washed with distilled water, and dried at 60 °C for 72 h [24].

Preparation and formulation of bioplastics

Separated solutions of LG and Ch were prepared at room temperature and then mixed to produce bioplastics through the casting method. LG was dissolved in an 80% (m/m) aqueous solution of acetic acid using magnetic stirring (700 rpm) for 20 min, and Ch was solubilized in a 2% (m/m) aqueous solution of acetic acid with magnetic stirring (450 rpm) for 4 h. Both solutions remained at rest during 20 h, and then were mixed with the plasticizer (20% m/m of the total mass of LG plus Ch) in an Erlenmeyer flask during 30 min at room temperature and 350 rpm. Later, the filmogenic solution (containing glycerin, Ch, and LG) was sonicated during 30 min to eliminate bubbles, then rested at room temperature for 30 min, and finally filtered through a 100 mesh sieve. All the bioplastic formulations used 0.705 g of filmogenic solution per cm^2 of acrylic plate area, and the drying stage was performed at 37 °C for 2 days. Table 1 exhibits the mass proportions used to prepare the bioplastics, in every formulation the filmogenic solution concentration of both components (Ch + LG) was maintained at 1% (m/v).

Characterization of bioplastics

Moisture and water solubility

Rectangular samples of 1.0 × 5.0 cm were cut (in triplicate) from each formulation and weighed (m_1). Then, the same samples were re-weighed after drying at 105 °C

Table 1 Formulations of the bioplastics (mass proportions in dry basis)

Sample	Ch (%)	LG (%)
Ch100LG0	100	0
Ch98LG2	98	2
Ch96LG4	96	4
Ch94LG6	94	6
Ch92LG8	92	8
Ch90LG10	90	10

Ch (%): Mass percentage of chitosan; LG (%): Mass percentage of lignin

during 24 h (m_2). To determine the moisture mass percentage (M), the difference between m_1 and m_2 was calculated (Eq. 1). Subsequently, each dried sample was immersed in 50 mL of distilled water, and the system was then shaken for 24 h at 110 rpm and 25 °C. After completing the immersion, the samples were withdrawn from the water, dried at the same conditions mentioned above, and weighed (m_3). Considering the difference between m_2 and m_3, the water solubilization percentage (S) was calculated using Eq. 2 [29].

$$\mathrm{M} = \frac{\mathrm{m_1} - \mathrm{m_2}}{\mathrm{m_1}} \cdot 100 \tag{1}$$

$$\mathrm{S} = \frac{\mathrm{m_2} - \mathrm{m_3}}{\mathrm{m_2}} \cdot 100 \tag{2}$$

Opacity

Rectangular samples of 0.9 × 3.0 cm were cut (in triplicate) from each formulation. Then, with a digital micrometer (0.001 mm accuracy) the thickness was measured at three different points (ends and center). After measuring the thickness, absorbance at 600 nm was read using a spectrophotometer, and the opacity (mm^{-1}) was calculated dividing the absorbance by the thickness [30].

Swelling (water absorption)

Rectangular samples of 1.0 × 4.0 cm were cut (in triplicate) from each formulation, dried at 50 °C during 24 h, and then weighed (m_1). Subsequently, each dried sample was soaked in 25 mL of distilled water for 24 h at 23 °C. After the soaking stage, the samples were withdrawn from the water, wiped off with filter paper (to remove the surface water), and then weighed (m_2). Then, the samples were dried under the same conditions mentioned above and again weighed (m_3). The percentage of increase in weight during soaking (%IW) was calculated using the mass difference between m_1 and m_2 (Eq. 1), and the percentage of water-soluble matter lost (%WS) was calculated using the mass difference between m_1 and m_3 (Eq. 2). The mass percentage of water absorption (%AB) corresponded to the sum of %IW and %WS (Eq. 3) [31, 32].

$$\%IW = \frac{m_2 - m_1}{m_1} \cdot 100 \tag{1}$$

$$\%WS = \frac{m_1 - m_3}{m_1} \cdot 100 \tag{2}$$

$$\%AB = \%IW + \%WS \tag{3}$$

Tensile test

Prior to testing, all formulations were conditioned for 48 h in an environment with a temperature of 23 °C and relative humidity of 56–57%. $Ca(NO_3)_2{\cdot}4H_2O$ (calcium nitrate tetrahydrate) inside a desiccator maintained the mentioned humidity, and an incubator controlled the temperature. After the conditioning stage, the tensile assay was completed as follows: ten strips of 1.0 cm width and 10 cm length were cut from each formulation, and every strip thickness was measured at 10 different places using a digital micrometer (0.001 mm accuracy) [33]. All tests took place with a load cell of 5 kg, a movement speed of 5 mm/min, and using a TXT-ENG-5 K testing machine. During tensile assays, the grips held 0.9 cm of each strip on either side, leaving 8.2 cm of free length. Based on the standard test method ASTM D882-18, the tensile properties were calculated, including tensile strength, elongation at break, and Young´s modulus.

Thermogravimetric analysis (TGA)

An equipment TGA Q500 (TA Instrument) analyzed the thermal stability of the Ch100LG0, Ch98LG2, and Ch90HC10 formulations. The thermogravimetric analysis was conducted in a nitrogen atmosphere (flow rate of 50 mL/min) over a range of temperatures between 25 and 800 °C (heating rate of 10 °C/min). The obtained thermograms represented the thermal behavior of the analyzed formulations.

Scanning electron microscopy (SEM)

The analysis of the surface and cross-sectional (cryofracture in nitrogen) morphology of the bioplastics Ch100LG0 and Ch90LG10 was conducted using an FEI Magellan 400 L XHR equipment. The images were obtained with an acceleration voltage of 2.0 kV, work distance of 5.0–6.0 mm, and magnifications of 100000x, 50000x, and 3000x.

Fourier Transform Infrared (FTIR) spectroscopy

To verify the intermolecular interaction of hydrogen bonding between Ch and LG in films, FTIR spectra were obtained using 32 scans and a resolution of 4 cm^{-1} throughout the region 4000–400 cm^{-1}. The commercial Ch (C3646 of Sigma-Aldrich) and the extracted LG were analyzed by the KBr pellet method (KBr: sample mass ratio of 1:125), and the Ch100LG0 and Ch94LG6 films were directly placed in the sample holder of the equipment (Attenuated Total Reflectance, IRAffinity-1 S Shimadzu). All spectra were normalized by maximum intensity method, and baseline correction was applied using the 3-point process.

Statistical analysis

The statistical analysis took place using the software IBM SPSS version 28.0. The Tukey HSD test was used to verify significant differences among the formulations at a 95% confidence level ($p < 0.05$).

Results and discussion

Appearance of the bioplastics

All bioplastic preparations exhibited a single phase, flexibility, and consistent structure without cracks, tears, or wrinkles (Fig. 1). However, the intensity of color proportionally increased with the content of added LG. All bioplastics with LG addition exhibited a heterogeneous color distribution, possibly attributable to the accumulation of LG in certain regions but without formation of aggregates. The observed behavior could be caused by several factors, such as partial compatibility between Ch and LG, mild mixing conditions (30 min at room temperature and 350 rpm), non-uniform evaporation of solvents during the drying period, or because the chemical

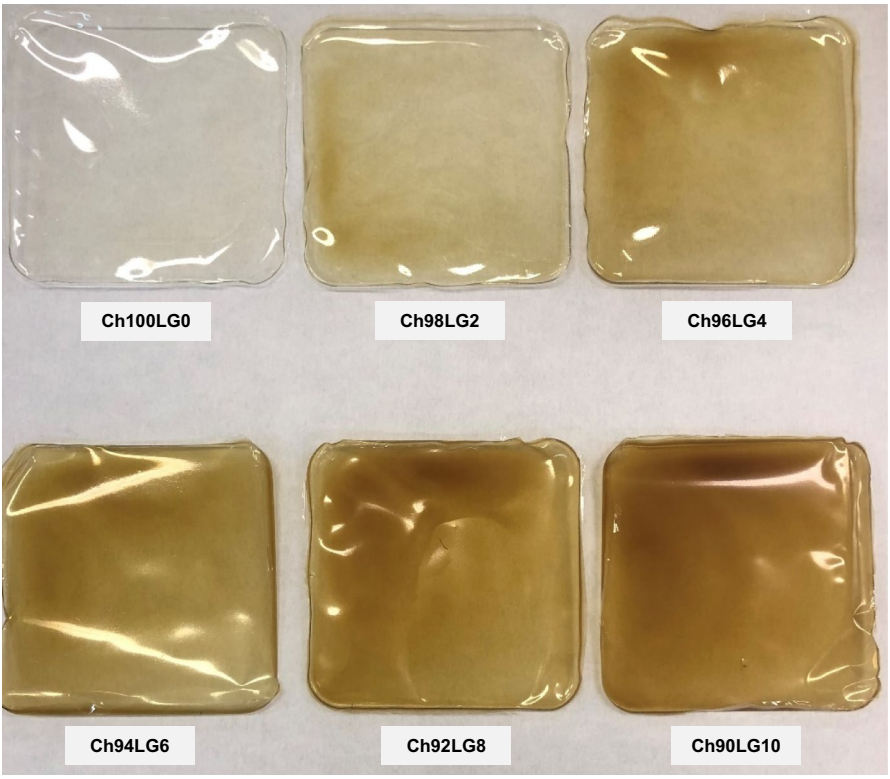


Fig. 1 Chitosan-lignin bioplastics using the different mass proportions listed in Table 1

interactions (bonds) among LG molecules were stronger than the linkages between LG and Ch. Chen et al. (2009) [34] suggested good compatibility of both components, probably caused by a strong intermolecular interaction in blend films containing 10–30% of LG. However, Rosova et al. (2021) [35] reported thermodynamic incompatibility between Ch and LG in composite films containing 10–30% of LG, but using water as a solvent to solubilize LG.

Characterization of bioplastics

Fourier Transform Infrared (FTIR) spectroscopy

FTIR spectra (Fig. 2) contributed to verify the formation of hydrogen bonding between Ch and LG in the films. The observed and analyzed region was 900–4000 cm^{-1}. The 1545 cm^{-1} band indicated hydrogen bonding established between OH groups present in LG and amide II group present in Ch. Likewise, the 1645 cm^{-1} band marked hydrogen bonding presence developed by OH groups of LG and amide I groups present in Ch [36]. Pure LG and Ch did not show the mentioned bands, which confirmed that films incorporating LG developed hydrogen bonds between their components. The identified hydrogen bonds could contribute to the improvement in the film properties,

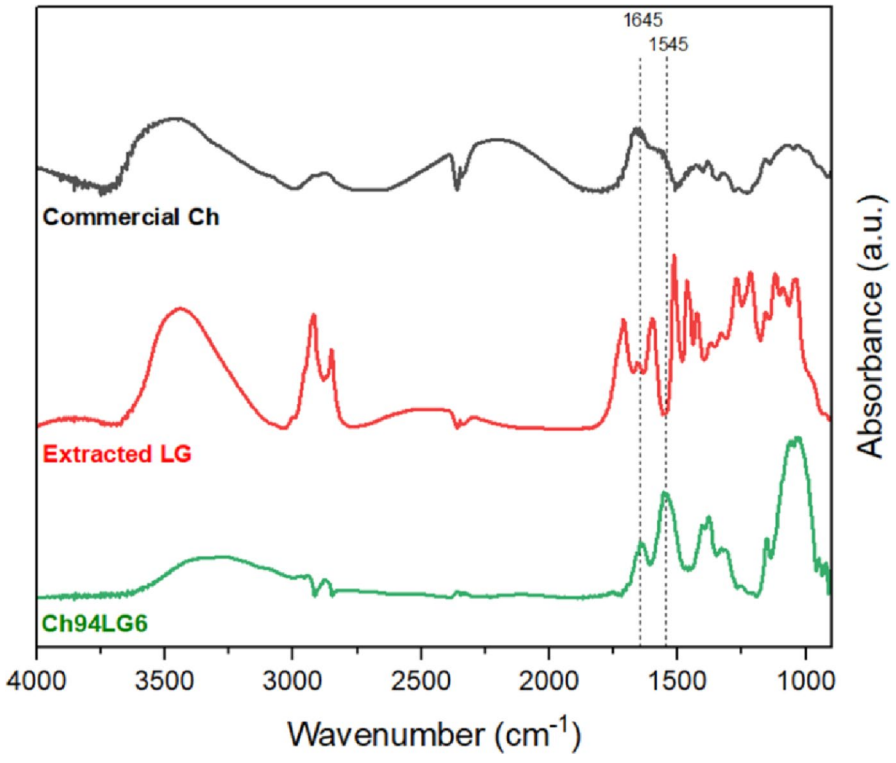


Fig. 2 Fourier Transform Infrared (FTIR) spectra of commercial Ch, extracted LG, and Ch94LG6 film

such as mechanical and thermal resistance, and swelling control. Figure 3 illustrates the possible interaction originated by hydrogen bonding in the complex Ch-LG.

Moisture and water solubility

Although there was a small variation in the moisture values among all formulations, those with LG incorporation showed moisture contents slightly higher than that made only of Ch (15.7%) (Fig. 4). The bioplastic with the highest content of added lignin (Ch90LG10) exhibited the highest moisture (19.4%) and was statistically different from Ch100HC0 (the only-Ch bioplastic). This behavior was in concordance with the Li et al. (2023) [36] study, which reported an increase in moisture contents when LG was added (mass proportions of 1–3%) to Ch-based films, however, the LG resulted from bagasse through deep eutectic solvents. Although LG is known to be hydrophobic in nature, its structure contains hydroxyl groups in aliphatic (R-OH), phenolic (Ph-OH), and carboxylic (R-COOH) sites, which have a chemical affinity with water (to form hydrogen bonds) due to the distribution of uneven charge in -OH groups [37, 38]. Besides these groups, the three-dimensional, heterogeneous, highly cross-linked, and branched structure of LG could provide a large surface area to possibly form hydrogen bonding with water molecules. On the other hand, when an aqueous solution of acetic acid solubilizes Ch, the amino groups ($-NH_2$) of the glucosamine molecules undergo protonation reactions. This fact results in a partial distribution of positive charges, which contribute to the repulsion of hydroxyl groups, decreasing the formation of hydrogen bonds with water molecules [39]. Therefore, the higher

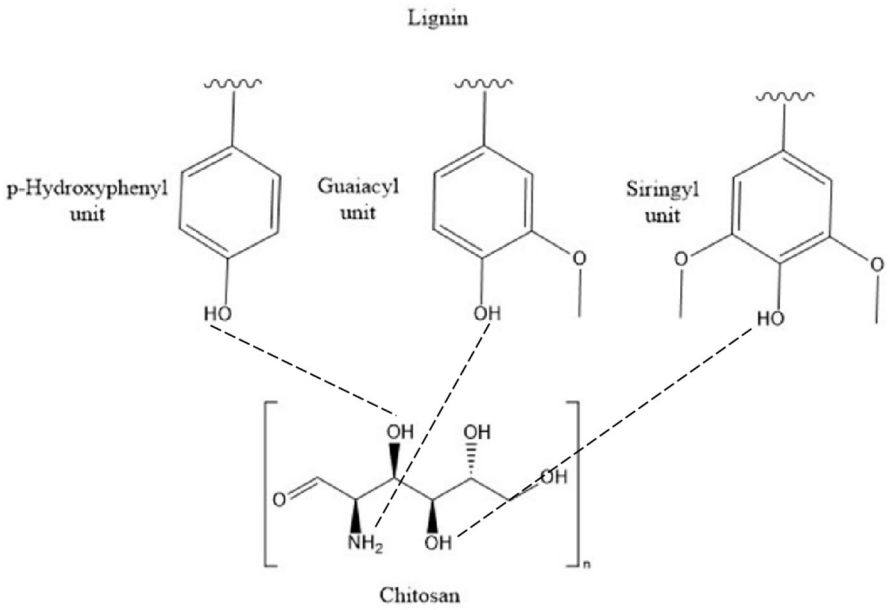


Fig. 3 Schematic diagram of possible hydrigen bonds developed between LG and Ch in the produced films

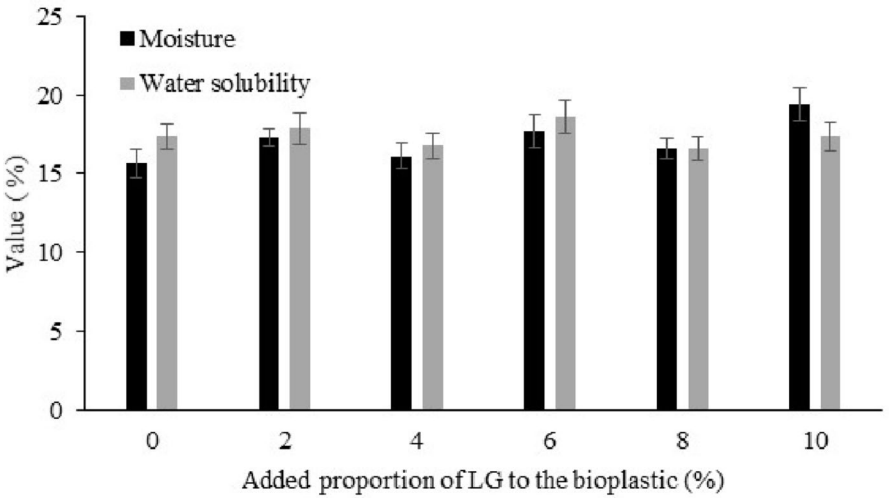


Fig. 4 Moisture and water solubility of the six preparations of bioplastics

the deacetylation degree of chitosan, the higher the presence of glucosamine units and the lower the presence of N-acetyl-glucosamine units, which would lead to more protonation reactions, increasing positive charges that would repel -OH groups of the water, reducing the number of hydrogen bonds. The moisture (15.7%) for the only-Ch bioplastic preparation (Ch100LG0) was slightly lower than those found by Leceta et al. (2013) [39], who reported values of 17.0 and 20.8% for films made of high and low molecular weight Ch (both with a degree of deacetylation higher than 75%), respectively, plasticized with glycerin (15% of mass proportion), and manufactured through the casting method. Conversely, Janik et al. (2021) [40] reported a moisture content of around 10% for a bioplastic plasticized with glycerin (21.2% of mass proportion), manufactured through mechanical blending and hot-pressing, and made of commercial dealkaline LG (mass percentage of 6.5%), commercial Ch (deacetylation degree higher than 90%) and starch (mass percentage of 18.8%).

In relation to the water solubility results, there were no statistically significant differences, and the range of values was 16.6–18.6%. This range was in agreement with the findings informed by Zou et al. (2023) [41], who reported water solubility values of 15.2 and 18.3% for Ch-based films with 1% and 5% of added LG, respectively. Both components were of commercial type, and the films were processed using the casting method. Likewise, the highest water solubility found in the present work (18.6%) was similar to 21.6%, value reported by Aradmehr et al. (2020) [42] for a film produced by the casting method, and composed of commercial Ch and LG (with a mass proportion of 25%) extracted from bagasse waste through the acidic-dioxane method. On the contrary, higher values of solubility have been reported for bioplastics that used LG as an additive and a base different from Ch. Michelin et al. (2020) [43] found solubilities ranging from 23.6 to 34.0% for bioplastics produced through the casting method, and using a commercial type of sodium carboxymethyl-cellulose and LG with contents of 12.5–50%. The determination of water solubility

is important because the performance of bioplastics based on natural polymers could be limited, particularly in food packaging applications [44].

Opacity

All formulations were statistically different and showed a positive strong linear correlation ($R = 0.95$) with the increasing of LG content (Fig. 5). The formulation containing 10% of LG exhibited the highest opacity value (4.92 mm^{-1}). The observed correlation agreed with Li et al. (2023) [36], who reported transmittances (200–800 nm range) of Ch-based films containing LG lower than the only-Ch film. The LG resulted from bagasse powder using different deep eutectic solvents, the range of LG content was 1–3%, and the films were produced in a coating machine without plasticizer addition. Bioplastics with reduced transmittance (increased opacity) would offer potential benefits related to product protection from photochemical reactions provoked by light exposure (UV rays). To preserve the properties (physical, chemical, and biological) of products, such as food, medicines, or beverages, bioplastics offering light protection are being developed [45]. However, to use opaque (or shady) bioplastics could impact the market since some consumers prefer to directly see the product inside its packaging before they open it [46]. The increase in opacity of Ch-based films with LG incorporation is attributed to the intense color of LG, which enhances UV absorption due to its aromatic groups, and to the formation of hydrogen bonds between LG and Ch [47].

Swelling (water absorption)

After the soaking period, all preparations remained intact and were carefully handled to avoid damage. Visually, the swollen bioplastics exhibited increased flexibility, which could be beneficial for specific applications or disadvantageous due to modifications in their mechanical properties. Formulations with LG (Ch98LG2 –

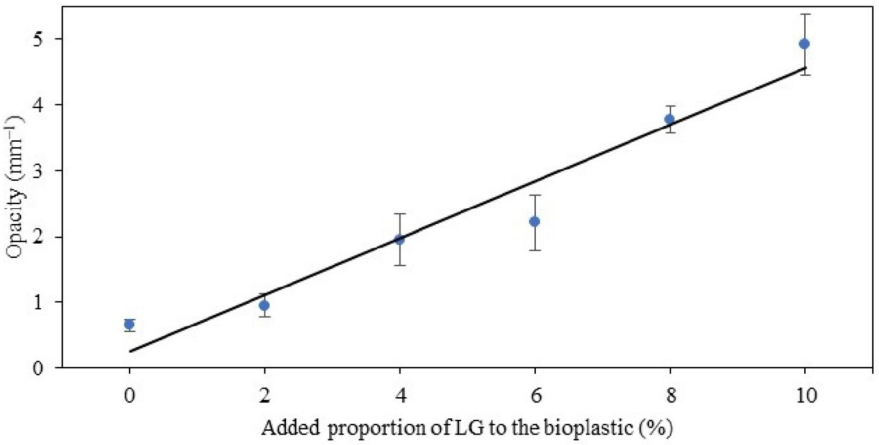


Fig. 5 Opacity values of the six preparations of bioplastics and linear correlation between added proportions of LG and opacity

Ch90LG10) showed swelling percentages lower than the bioplastic made only of Ch (Ch100LG0) (Fig. 6). Among them, the formulation with the highest content of LG (Ch90LG10) exhibited the minimum swelling (133.5%) and was statistically different from Ch100LG0. Additionally, swelling showed an inverse linear correlation ($r = 0.83$) with the increase of LG content (Fig. 6). The swelling of solid materials results from the movement of water molecules through internal spaces in the solid. This internal transport phenomenon occurs by mass diffusion, a mechanism where the movement of water molecules obeys their concentration gradient until it achieves an equilibrium concentration [48]. Thus, the mass diffusion of water within the structure provoked the bioplastic molecules to separate, generating expansion in the material. However, the formulations with LG incorporation probably hindered the water diffusion, provoking the swelling reduction. LG molecules likely occupied or blocked some spaces within the bioplastic structure, impeding the formation of hydrogen bonds between water and Ch. Moreover, the gradual replacement of the Ch amounts with LG, as well as the hydrophobic nature of LG, could also be responsible for the swelling reduction.

The lowest swelling (133.5%), corresponding to the preparation with the maximum content (10%) of LG, which was slightly higher than that reported by Chen et al. (2009) [34], who found a value of 124% for a film (without plasticizer) manufactured from commercial Ch (deacetylation degree 90%) and LG, through the casting method, preparing individual solutions (Ch and LG), 10% of LG content, and including a drying stage in an oven at 50 °C. Likewise, according to Janik et al. (2021) [40], the incorporation (5.2%) of dealkaline commercial LG in a bioplastic formed by Ch (high molecular weight), starch, and PVA (Elvanol 71–30), and processed through hot-pressing with glycerin plasticizer, resulted in a decrease in the swelling percentage from 200 to 90%. Conversely, the research of Aradmehr et al. (2020) [42] reported a higher swelling value (around 175%) for a film made of commercial Ch and acidic-dioxane LG extracted from bagasse wastes (content of 25%). This film

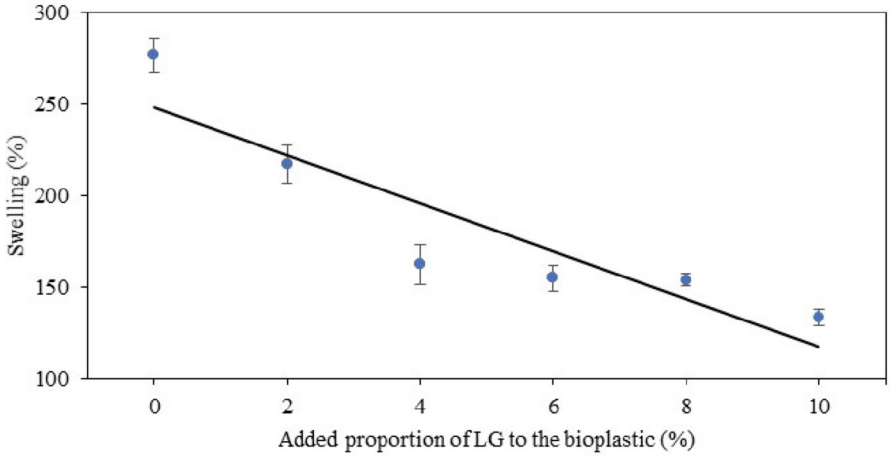


Fig. 6 Swelling values of the six preparations of bioplastics and linear correlation between added proportions of LG and swelling

was obtained through the casting method and included 0.03% of silver particles and glutaraldehyde as a cross-linking agent. Bioplastics with reduced swelling probably indicate hydrophobicity presence (caused by the diminishing of water diffusion) and slower degradation rates (caused by the limitation of oxidation processes) [49, 50].

Tensile strength

Results of the tensile properties of the six preparations of bioplastics are showed in Fig. 7. The formulations with LG content showed tensile strength values higher than that made of Ch 100% (12.5 MPa). The formulation Ch94LG6 (94% of Ch and 6% of LG) had the highest tensile strength (22.5 MPa) and was statistically different from the formulation Ch100HC0 (100% of Ch). The difference in resistance to lengthwise stress between the formulations Ch94LG6 and Ch100HC0 could be explained by the formation of hydrogen bonds between Ch and LG, which possibly contributed to enhancing the tensile strength [6]. Chen et al. (2009) [34] also observed an improvement in tensile strength when LG contents of 5–20% were incorporated in Ch-based films. Likewise, Jaganathan et al. (2018) [21] observed the same behavior for LG contents of 1–5% in Ch-based films, the formulation with the highest content of LG (5%) showed the maximum tensile strength (0.69 MPa). However, this value was very low compared to the highest one found in the present work (22.5 MPa) with a similar LG content (6%). Rai et al. (2017) [50] revealed a tensile strength of 22 MPa for a film made of Ch (79% deacetylated) and 10% LG (extracted by an alkali route from sugar cane bagasse). The film processing took place using the casting method but without the use of any plasticizer, and the solid LG was directly added to the Ch solution. Li et al. (2023) [36] reported a tensile strength (21.3 MPa) slightly lower than the maximum one found in the present research. The value was obtained for two

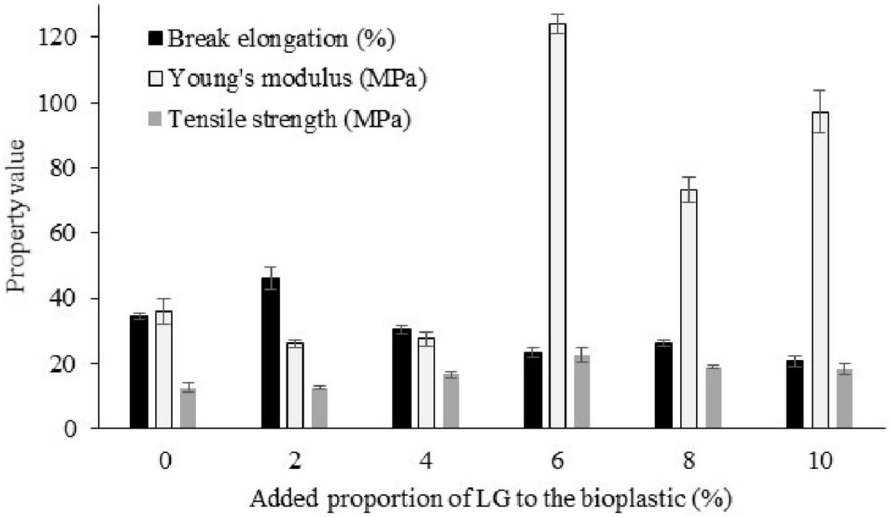


Fig. 7 Tensile strength (MPa), breaking elongation (%) and Young´s modulus (MPa) of the six preparations of bioplastics

bioplastics obtained through the casting method and made of commercial Ch and LG (extracted from sugarcane bagasse by chlorine chloride-urea solvent) with 2 and 3% of LG.

Although the maximum tensile strength observed in the present study was similar to those reported in the cited literature, some studies have revealed superior values. Rosova et al. (2021) [35] produced a film with a tensile strength of 54.6 MPa from 80% of commercial Ch (86.5% of deacetylation degree) and 20% of industrial LG (extracted from softwood and modified by a hydrothermal alkaline process). The film processing took place using the casting method (including degassing) without any plasticizer, the filmogenic solution resulted from mixing individual solutions (Ch and LG), and the drying stage occurred at room temperature. And, Aradmehr et al. (2020) [42] reported a tensile strength of around 47 MPa for a film produced with commercial Ch and 25% of acidic-dioxane LG (extracted from bagasse waste), using the casting method, but including 0.03% of silver particles and glutaraldehyde as cross-linking agent. The film processing also involved preparing the filmogenic solution by mixing individual solutions (Ch and LG) and oven-drying at 50 °C.

Breaking elongation

The formulations containing LG (except for Ch98LG2) showed breaking elongation values lower than those made entirely of Ch (34.6%). The formulation with the maximum content of LG (Ch90LG10 = 90% of Ch and 10% of LG) revealed the lowest elongation (20.7%), and it was statistically different from the formulation Ch100HC0 (100% of Ch). In recent research, LG was used as an additive in several bioplastics to improve their tensile strength due to LG can provide rigidity to the polymeric network. However, LG incorporation can affect the elongation of films [51, 52]. Thereby, the bioplastics containing LG (except the Ch98LG2) were more rigid than the only-Ch formulation. The exception one, composed of 98% Ch and 2% LG (Ch98LG2), exhibited the highest elongation at break (46.2%), which was in great accordance with the findings of Li et al. (2023) [36]. The research reported that the maximum value (approximately 62%) resulted when 2% of LG was added to Ch-based films. The film processing involved a coating machine without plasticizer use, and LG extraction was from bagasse powder through a deep eutectic solvent. The same research also informed that a film produced from 99% of Ch and 1% of LG (extracted using choline chloride mixed with lactic acid) had the minimum value (around 19%) of elongation at break. Regarding the maximum elongation at break found in the present research (46.2%), Chen et al. (2009) [34] reported a slightly higher value (around 48%), which corresponded to a bioplastic obtained through the casting method, and made of commercial Ch and 5% of LG. In contrast, Rosova et al. (2021) [35] found values below 9.5% for Ch-based films containing 10–30% of LG. Ch with an 86.5% deacetylation degree was the commercial type and LG came from industry. The film manufacturing occurred without plasticizer addition, through the casting method, and the filmogenic solution resulted from mixing the individual solutions (Ch and LG).

Although the highest elongation at break achieved in the present study was around those found in the studies cited above, other studies reported higher values. Arad-

mehr et al. (2020) [42] found a maximum breaking elongation of around 65% for a film manufactured through the casting method and produced with commercial Ch and 25% of acidic-dioxane LG extracted from bagasse wastes. The film production also included 0.03% silver particles, glutaraldehyde as a cross-linking agent, preparation of filmogenic solution from individual solutions (Ch and LG), and oven-drying at 50 °C. And, Luo et al. (2023) [6] developed a film with a maximum elongation at break of 73.6% from 95% of commercial Ch (90% of deacetylation degree) and 5% of highly sulfomethylated LG. LG resulted from softwood kraft black liquor and posterior chemical modification, and the film processing was through the casting method without a plasticizer.

Values of elongation at break, such as those informed by Luo et al. (2023) [6] and Aradmehr et al. (2020) [42], mean the bioplastics made of Ch and LG had the property to withstand high longitudinal deformations before they broke. In contrast, the low values of elongation at break reported in the Rosova et al. (2021) [35] study suggested the films were prone to fractures [53]. Hence, the maximum elongation at break found in the present work could be regarded as an intermediate value, because it was higher than those informed by Rosova et al. (2021) [35] and lower than those revealed by Luo et al. (2023) [6] and Aradmehr et al. (2020) [42].

Young's modulus

The formulations containing 2 and 4% of LG exhibited Young's moduli smaller than the one made of Ch 100%, in contrast, the preparations containing 6, 8, and 10% of LG had higher values. Among them, the formulation containing 6% of LG (Ch94LG6) showed the highest Young's modulus (124.0 MPa), and it was statistically different from the other. The most rigid formulation (the Ch94LG6) probably developed more hydrogen bonds between Ch and LG, which potentially contributed to obtaining a tight chemical structure [6]. Crouvisier-Urion et al. (2016) [53] reported a similar Young's modulus value (130 MPa) for a Ch-based film with 20% of LG and produced through the casting method (without plasticizer). LG came from sugarcane using an alkali process, Ch was of commercial type with a 90% deacetylation degree, and solutions of ethanol and acetic acid solubilized LG and Ch, respectively. This same study reported Young's modulus of 100 MPa for a film with 10% of LG. On the contrary, Jaganathan et al. (2018) [21] reported values below 0.7 MPa with LG contents of 1–5% in Ch-based films. The mentioned research also reported elongation at break values of 29.8–42.6% and a range of tensile strength of 0.43–0.69 MPa. Although the highest Young's modulus reported in the present study was around those found in the studies cited above, Rosova et al. (2021) [35] informed higher values (2.75–2.84 GPa) for formulations made from Ch and LG (contents of 10–30%). However, the films exhibited low values of elongation at break (8.8–9.4%). High values of Young's modulus mean that a specific material has high stiffness; however, Ch-based bioplastics with this characteristic can result in a reduction of their elongations [6, 53].

Thermogravimetric analysis (TGA)

In food packaging applications, the thermal behavior analysis of bioplastics is important when they are used as materials for storage or preservation at different temperatures [54]. Hence, the influence of LG incorporation in the Ch-based bioplastics was studied using TGA (Fig. 8). The curves in Fig. 8a correspond to mass loss thermograms of the formulations Ch100LG0, Ch98LG2, and Ch90LG10. All of them exhibited four degradation stages, where the first one corresponded to the evaporation of acetic acid and water between 25 and 120 °C, a range in which the three formulations had a mass average loss of approximately 16.3% [34, 55]. The second stage showed the degradation of Ch low molecular weight fractions and glycerol in the temperature range of 125–310 °C, during which a mass average loss of around 16.7% occurred [56]. The third stage occurred between 310 and 400 °C, this range corresponded to the Ch decomposition and LG depolymerization, and the mass average loss reached its maximum value (28.2%) [57, 58]. Finally, the temperature range > 400 °C corresponded to the fourth stage, during which the film carbonization occurred, and a mass average loss of roughly 8.8% took place [59]. At the end of the first stage, the formulation Ch90LG10 showed a slight decrease in mass loss compared to the other ones. During the second and final stages, the formulation Ch98LG2 exhibited a small increase in mass loss. However, in the third stage, the bioplastics with LG content did not show any increase or decrease compared to the formulation Ch100HC0. Li et al. (2023) [36] also reported four stages of mass loss for films produced with Ch and LG, however, the LG used was from sugarcane bagasse (extraction using chlorine chloride-urea solvent), and the formulations incorporated 0.5–3% of LG. The observed temperature ranges were < 100 °C, 100–210 °C, 210–420 °C and > 420 °C.

On the other hand, Fig. 8b shows that the LG addition caused an increase (Δ) of 3 °C in the temperature at which the highest mass loss occurred (T_{MAX}). 330.5 °C was the T_{MAX} for the formulation Ch100LG0, 333.4 °C for Ch98LG2, and 333.6 °C for Ch90LG10. Nevertheless, the degradation thermal rate (%/°C) at T_{MAX} for the bioplastics with LG content were slightly lower than the only-Ch formulation. Aradmehr et al. (2020) [42] also reported an increase in T_{MAX} when LG was added to Ch-based

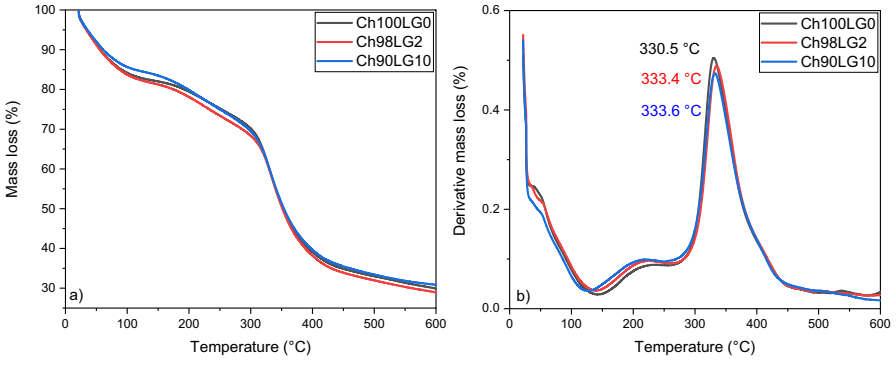


Fig. 8 (**a**) Thermogravimetric (TG) and (**b**) derivative thermogravimetric (DTG) curves of the formulations Ch100LG0, Ch98LG2 and Ch90LG10

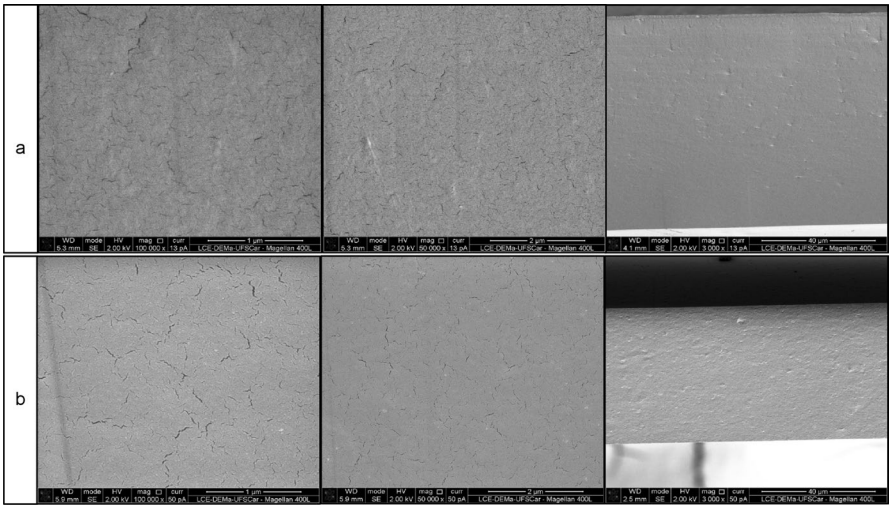


Fig. 9 Scanning electron microscopy images of the formulations Ch100LG0 (**a**) and Ch90LG10 (**b**) with different magnification (100000x, 50000x, and 3000x)

bioplastics, which could indicate a stabilizing effect (probably caused by LG) on the thermal degradation of such bioplastics. Similarly, Luo et al. (2023) [6] reported an increase in T_{MAX} for a Ch-based film incorporating 7% of sulfomethylated LG, however, the ΔT_{MAX} was of 10.3 °C. And, Chen et al. (2009) [34] also informed a ΔT_{MAX} = 3 °C for a bioplastic obtained through the casting method and made of 80% of Ch and 20% of LG.

Scanning electron microscopy (SEM)

SEM showed the morphology of the formulations Ch100LG0 and Ch90LG10 using surface and cross-section images (Fig. 9). The Ch90LG10 bioplastic showed an even surface, where particles did not exhibit any form of aggregation, resulting in a good distribution of the LG in the non-crystalline sites of Ch [59]. Besides that, the Ch90LG10 had microfractures more visible than the only-Ch film. The cross-section SEM revealed the absence of holes, layer formation, and protrusions. The formulation containing LG exhibited a dense structure, likely due to the complete dispersion of LG within the Ch matrix [6]. The films that incorporated LG (at the range used in the present study) into the Ch matrix can be cataloged as blends, since the structural observation gave signs of good cohesion between Ch and LG.

Conclusions

All proposed formulations resulted in thin bioplastics with one-phase, flexible, and consistent structure. The LG addition to Ch-based films led to changes in their physical and mechanical properties. The gradual inclusion of LG caused a color variation and a heterogeneous dispersion/distribution of color. The results of water solubility

showed no statistically significant variations. Regarding opacity, the results were statistically different, and a strong positive linear correlation revealed that the gradual increase of LG content led to an increase in the opacity. In terms of swelling, an inverse linear correlation revealed that the same gradual increase of LG content led to a decrease in the swelling values. The LG addition to the bioplastics improved the tensile strength values but decreased the elongation at break. The formulation with the highest LG addition showed the lowest value of elongation at break. According to TGA, the analyzed samples had mass loss in four distinct steps, the LG incorporation raised the temperature at which the bioplastics had their maximum mass losses, and the lowest mass loss rate was observed in the preparation with the maximum amount of added LG. The opacity and swelling can be considered promising properties since they showed mathematical dependence on the added LG content, which could be observed by the linear models. As a result, the possible applications of this kind of bioplastics could be in the food or medicine fields, since the control of light exposure and water diffusion are considered key factors.

Author contributions Conceptualization, MB and HDZZ; methodology, HDZZ, MB, HF, RMV, and AP; validation, HF, and AP; formal analysis, HDZZ; resources, MB, and HF; writing—original draft preparation, HDZZ; writing—review and editing, MB, HF, and AP; supervision, MB. All authors have read and agreed to the published version of the manuscript.

Funding The Article Processing Charge (APC) for the publication of this research was funded by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) (ROR identifier: 00x0ma614). This research received support from Brazilian National Council for Scientific and Technological Development (CNPq process number 305078/2025-9; 403481/2025-2), São Paulo Research Foundation and Netherlands Organisation for Scientific Research and (NWO-FAPESP, 2021/10839-4), and Federal Ministry of Education and Research (BMBF-Fapesp, 2024/21365-1), Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – project 525894115 within the Priority Program SPP 2416 "Codeχ – The code of chito-protein interactions" and Federal Ministry of Food and Agriculture (BMEL) based on a decision of the parliament of the Federal Republic of Germany via the Federal Office for Agriculture and Food (BLE) under the Federal Programme for Ecological Farming.

Data availability The data that support the findings of this study are available on request.

Declarations

Conflict of interest The authors declare no competing interests.

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References

1. OECD (2023) Global Plastics Outlook: Plastics use by polymer - projections. https://www.oecd-ilibrary.org/environment/data/global-plastic-outlook_c0821f81-en. Accessed 6 Apr 2023
2. Plastics E (2022) Plastics-The facts 2021. Brussels
3. Conversio (2020) Global Plastics Flow 2018. Mainaschaff
4. OECD (2020) Global Plastics Outlook: Greenhouse gas emissions from primary plastics. https://www.oecd-ilibrary.org/environment/data/global-plastic-outlook_c0821f81-en. Accessed 6 Apr 2023
5. Abe MM, Branciforti MC, Nallin Montagnolli R et al (2022) Production and assessment of the biodegradation and ecotoxicity of xylan- and starch-based bioplastics. Chemosphere 287:1–10. https://doi.org/10.1016/j.chemosphere.2021.132290
6. Luo J, Gu Y, Yuan Y et al (2023) Lignin-induced sacrificial conjoined-network enabled strong and tough chitosan membrane for food preservation. Carbohydr Polym. https://doi.org/10.1016/j.carbpol.2023.120876
7. Ponnusamy PG, Mani S (2022) Material and environmental properties of natural polymers and their composites for packaging applications-a review. Polymers (Basel) 14:1–22. https://doi.org/10.3390/polym14194033
8. Gent S, Twedt M, Gerometta C, Almberg E (2017) Chapter Two - Introduction to Feedstocks. In: Gent S, Twedt M, Gerometta C, Almberg EBT-T, AA of BT (eds) Theoretical and Applied Aspects of Biomass Torrefaction. Butterworth-Heinemann, Oxford, pp 17–39
9. Jacob J, Gomes F, Haponiuk JT (2022) Natural Polymers: Perspectives and Applications for a Green Approach, 1st ed. Taylor & Francis Group, London
10. Amaraweera SM, Gunathilake C, Gunawardene OHP et al (2021) Development of starch-based materials using current modification techniques and their applications: a review. Molecules 26:1–30. https://doi.org/10.3390/molecules26226880
11. Priyadarshi R, Rhim J-W (2020) Chitosan-based biodegradable functional films for food packaging applications. Innov Food Sci Emerg Technol 62:1–20. https://doi.org/10.1016/j.ifset.2020.102346
12. Agrawal R, Kumar A, Singh S, Sharma K (2022) Recent advances and future perspectives of lignin biopolymers. J Polym Res 29:222. https://doi.org/10.1007/s10965-022-03068-5
13. Schmatz AA, Tyhoda L, Brienzo M (2020) Sugarcane biomass conversion influenced by lignin. Biofuels Bioprod Biorefin 14:469–480. https://doi.org/10.1002/bbb.2070
14. Liu Q, Luo L, Zheng L (2018) Lignins: biosynthesis and biological functions in plants. Int J Mol Sci 19:1–16. https://doi.org/10.3390/ijms19020335
15. Ganewatta MS, Lokupitiya HN, Tang C (2019) Lignin biopolymers in the age of controlled polymerization. Polymers (Basel) 11:1–44. https://doi.org/10.3390/polym11071176
16. Li J, Tian X, Hua T et al (2021) Chitosan natural polymer material for improving antibacterial properties of textiles. ACS Appl Bio Mater 4:4014–4038. https://doi.org/10.1021/acsabm.1c00078
17. Duan J, Han C, Liu L et al (2015) Binding cellulose and chitosan via intermolecular inclusion interaction: synthesis and characterisation of gel. Journal of Spectroscopy 2015:1–6. https://doi.org/10.1155/2015/179258
18. Pellis A, Guebitz GM, Nyanhongo GS (2022) Chitosan: sources, processing and modification techniques. Gels 8:1–27. https://doi.org/10.3390/gels8070393
19. Ahsan SM, Thomas M, Reddy KK et al (2018) Chitosan as biomaterial in drug delivery and tissue engineering. Int J Biol Macromol 110:97–109. https://doi.org/10.1016/j.ijbiomac.2017.08.140
20. Fernandez JG, Ingber DE (2014) Manufacturing of large-scale functional objects using biodegradable chitosan bioplastic. Macromol Mater Eng 299:932–938. https://doi.org/10.1002/mame.201300426
21. Jaganathan G, Manivannan K, Lakshmanan S, Sithique MA (2018) Fabrication and characterization of *Artocarpus heterophyllus* waste derived lignin added chitosan biocomposites for wound dressing application. Sustain Chem Pharm 10:27–32. https://doi.org/10.1016/j.scp.2018.08.002
22. Angulo-López JE, Flores-Gallegos AC, Torres-León C et al (2021) Guava (*Psidium guajava* L.) fruit and valorization of industrialization by-products. Processes 9:1–17. https://doi.org/10.3390/pr9061075
23. Vieira RM, Gonçalves AR, Brienzo M (2024) Comprehensive chemical characterization study of three major fruit residues from São Paulo State (Brazil): banana pseudostem, orange bagasse, and guava seed cake. J Mater Cycles Waste Manag. https://doi.org/10.1007/s10163-024-02057-8

24. Zamora Zamora HD, de Freitas C, Pasquini D et al (2024) Enhanced fractionation of guava seed cake using alkali-catalyzed ethanol organosolv pretreatment. BioEnergy Res 18:1–13. https://doi.org/10.1007/s12155-024-10813-9
25. Sirbu E-E, Dinita A, Tănase M et al (2024) Influence of plasticizers concentration on thermal, mechanical, and physicochemical properties on starch films. Processes 12:2021. https://doi.org/10.3390/pr12092021
26. Zamora Zamora HD, Ferreira H, Pich A, Brienzo M (2024) Hemicellulose additive to chitosan-based bioplastic improved the tensile strength and allowed to control the material swelling. Polym Bull 81:9265–9285. https://doi.org/10.1007/s00289-024-05152-w
27. Fernandes ÉS, Bueno D, Pagnocca FC, Brienzo M (2020) Minor biomass particle size for an efficient cellulose accessibility and enzymatic hydrolysis. ChemistrySelect 5:7627–7631. https://doi.org/10.1002/slct.202001008
28. Cardoso F, Castrillo VS, Bueno D, Schmatz AA, Freitas C, Brienzo M (2026). Modified organosolv process for obtaining hemicellulose and lignin. Patent BR 102020023093–0.
29. Medina-Jaramillo C, Ochoa-Yepes O, Bernal C, Famá L (2017) Active and smart biodegradable packaging based on starch and natural extracts. Carbohydr Polym 176:187–194. https://doi.org/10.1016/j.carbpol.2017.08.079
30. Zhao J, Wang Y, Liu C (2022) Film transparency and opacity measurements. Food Anal Methods 15:2840–2846. https://doi.org/10.1007/s12161-022-02343-x
31. ISO (2021) ISO 62:2008: Plastics - Determination of water absorption. Vernier
32. ASTM (2022) D570-22: Standard Test Method for Water Absorption of Plastics. West Conshohocken, United States
33. ASTM (2018) D882-18: Standard Test Method for Tensile Properties of Thin Plastic Sheeting. West Conshohocken
34. Chen L, Tang C, Ning N et al (2009) Preparation and properties of chitosan/lignin composite films. Chin J Polym Sci 27:739–746. https://doi.org/10.1142/S0256767909004448
35. Rosova E, Smirnova N, Dresvyanina E et al (2021) Biocomposite materials based on chitosan and lignin: preparation and characterization. Cosmetics Basel 8:1–17. https://doi.org/10.3390/cosmetics8010024
36. Li C, Zheng C, Huang H et al (2023) Preparation and plasticizing mechanism of deep eutectic solvent/lignin plasticized chitosan films. Int J Biol Macromol. https://doi.org/10.1016/j.ijbiomac.2023.124473
37. Guan M, An X, Zhang H et al (2022) Lignin emulsifying rosin for improved sizing performance and mechanical properties of liquid packaging board. Ind Crops Prod 187:1–11. https://doi.org/10.1016/j.indcrop.2022.115276
38. Luo Y, Wang Q (2014) Recent development of chitosan-based polyelectrolyte complexes with natural polysaccharides for drug delivery. Int J Biol Macromol 64:353–367. https://doi.org/10.1016/j.ijbiomac.2013.12.017
39. Leceta I, Guerrero P, de la Caba K (2013) Functional properties of chitosan-based films. Carbohydr Polym 93:339–346. https://doi.org/10.1016/j.carbpol.2012.04.031
40. Janik W, Wojtala A, Pietruszka A et al (2021) Environmentally Friendly Melt-Processed Chitosan/Starch Composites Modified with PVA and Lignin. Polym (Basel) 13:1–14. https://doi.org/10.3390/polym13162685
41. Zou Z, Ismail BB, Zhang X et al (2023) Improving barrier and antibacterial properties of chitosan composite films by incorporating lignin nanoparticles and acylated soy protein isolate nanogel. Food Hydrocoll 134:108091. https://doi.org/10.1016/j.foodhyd.2022.108091
42. Aradmehr A, Javanbakht V (2020) A novel biofilm based on lignocellulosic compounds and chitosan modified with silver nanoparticles with multifunctional properties: synthesis and characterization. Colloids Surf A Physicochem Eng Asp 600:1–8. https://doi.org/10.1016/j.colsurfa.2020.124952
43. Michelin M, Marques AM, Pastrana LM et al (2020) Carboxymethyl cellulose-based films: effect of organosolv lignin incorporation on physicochemical and antioxidant properties. J Food Eng 285:1–9. https://doi.org/10.1016/j.jfoodeng.2020.110107
44. Ezati P, Khan A, Priyadarshi R et al (2023) Biopolymer-based UV protection functional films for food packaging. Food Hydrocoll 142:1–17. https://doi.org/10.1016/j.foodhyd.2023.108771
45. Gil-Pérez I, Rebollar R, Lidón I (2020) Without words: the effects of packaging imagery on consumer perception and response. Curr Opin Food Sci 33:69–77. https://doi.org/10.1016/j.cofs.2019.12.006

46. Pham CD, Truong TM, Ly TB, Le PK (2024) Application of lignin from cellulose isolation process in the fabrication of chitosan/lignin film for UV-light blocking and anti-oxidation. Waste Biomass Valorization 15:1881–1894. https://doi.org/10.1007/s12649-023-02353-8
47. Bird RB, Stewart WE, Lightfoot EN (2002) Transport Phenomena, 2nd ed. John Wiley & Sons, New York
48. Nguyen TT, Thi Dao UT, Thi Bui QP et al (2020) Enhanced antimicrobial activities and physiochemical properties of edible film based on chitosan incorporated with *Sonneratia caseolaris* (L.) Engl. leaf extract. Prog Org Coat 140:1–9. https://doi.org/10.1016/j.porgcoat.2019.105487
49. Abe MM, Branciforti MC, Brienzo M (2021) Biodegradation of hemicellulose-cellulose-starch-based bioplastics and microbial polyesters. Recycling 6:1–21. https://doi.org/10.3390/recycling6010022
50. Rai S, Dutta PK, Mehrotra GK (2017) Lignin incorporated antimicrobial chitosan film for food packaging application. J Polym Mater 34:171–183
51. Duval A, Lawoko M (2014) A review on lignin-based polymeric, micro- and nano-structured materials. React Funct Polym 85:78–96. https://doi.org/10.1016/j.reactfunctpolym.2014.09.017
52. Callister WD, Rethwisch DG (2018) Materials Science and Engineering: An Introduction, 10th ed. Wiley, Hoboken
53. Crouvisier-Urion K, Bodart PR, Winckler P et al (2016) Biobased composite films from chitosan and lignin: antioxidant activity related to structure and moisture. ACS Sustain Chem Eng 4:6371–6381. https://doi.org/10.1021/acssuschemeng.6b00956
54. Moalla S, Ammar I, Fauconnier M-L et al (2021) Development and characterization of chitosan films carrying *Artemisia campestris* antioxidants for potential use as active food packaging materials. Int J Biol Macromol 183:254–266. https://doi.org/10.1016/j.ijbiomac.2021.04.113
55. Kamdem DP, Shen Z, Nabinejad O, Shu Z (2019) Development of biodegradable composite chitosan-based films incorporated with xylan and carvacrol for food packaging application. Food Packag Shelf Life 21:1–9. https://doi.org/10.1016/j.fpsl.2019.100344
56. Ge H, Wang S (2014) Thermal preparation of chitosan–acrylic acid superabsorbent: optimization, characteristic and water absorbency. Carbohydr Polym 113:296–303. https://doi.org/10.1016/j.carbpol.2014.06.078
57. Brebu M, Vasile C (2010) Thermal degradation of lignin – a review. Cellul Chem Technol 44:353–363
58. Li Z-C, Chen X, Zhang J-L et al (2024) Unlocking superior preservation: the synergy of lignin and zeolite in chitosan-based composite films for perishable foods. Food Packag Shelf Life 46:101362. https://doi.org/10.1016/j.fpsl.2024.101362
59. Lisý A, Ház A, Nadányi R et al (2022) About Hydrophobicity of Lignin: A Review of Selected Chemical Methods for Lignin Valorisation in Biopolymer Production. Energies (Basel) 15:1–27. https://doi.org/10.3390/en15176213

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