Characterization of starch-based bioplastics from jackfruit seed plasticized with glycerol

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Abstract Biodegradable films based on starches from different botanical sources exhibited physicochemical and functional properties which were related with the starch characteristics. However, had inadequate mechanical properties and were hard and brittle. In this research, jackfruit seed starch plasticized with glycerol were developed and characterized. The starch and glycerol concentrations ranged from 2 to 6% w/w and 20 to 60 g/100 g starch, respectively. Bioplastics were obtained by the casting method and characterized in terms of color, mechanical properties, solubility, water vapor permeability (WVP), morphology and free energy of the hydrophobic interaction. Electronic micrographics showed the presence of some intact starch granules. The bioplastics were hydrophilic and those of 6% starch and 40% glycerol were the most hydrophilic ($\Delta G_{sas}^{tot} = 41.35 \text{ mJ m}^{-1}$). The solubility of the films presented a direct relationship with the

starch concentration ranging from 16.42 to 23.26%. Increased opacity and color difference were observed with increasing starch concentration. The WVP ranged from 1.374×10^{-3} to $3.07 \times 10^{-4} \text{ g m/day m}^2$ which was positively related with the concentration of starch and glycerol. Tensile strength, percent elongation and Young's Modulus indicated that the jackfruit starch and glycerol provided a film with good mechanical properties. The results replaced that jackfruit starch can be used to develop films, with low opacity, moderate WVP and relatively high mechanical stability, by using glycerol in the gelatinized starch dispersions.

Keywords Biopolymers · Polysaccharides · Food preservation

Introduction

There has been increased interest in the development of biodegradable films because the environmental damage from conventional plastic packaging is increasingly evident (Fakhoury et al. 2012). Bioplastics are produced from 100% renewable raw material which, when discarded in conditions favorable to its decomposition, is rapidly integrated into nature as carbon dioxide, water and biomass (Telles et al. 2011). Biodegradable plastics are produced from biopolymers extracted directly from biomass, with or without modification, such as starch, cellulose and proteins (Jerez et al. 2007). Among these, starch has presented potential for the production of biodegradable materials because is a low-cost raw material, easily available and renewable (Mbey et al. 2012).

Starch-based biodegradable plastics are water-sensitive, have high water vapor permeability and generally provide

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films with mechanical properties unsuitable for many applications, which has hindered the expansion of their use and justifies the need to make modifications to improve their properties (Mbey et al. 2012). Biodegradable plastic properties can be improved mainly by using mixtures of starch with other synthetic polymers (Chen et al. 2014) and chemical and physical modifications (Zavareze et al. 2012; Singh and Nath 2013).

Thus, the use of alternative botanical sources may be an important strategy to improve the properties of starch-based biodegradable plastics. Among these sources, we can highlight the jackfruit seed. Jackfruit (*Artocarpus heterophyllus*) is a species of tree belonging to the Moraceae family, widely found throughout many tropical and subtropical regions such as India, Bangladesh, and in many parts of Southeast Asia (Suryadevara et al. 2017). The jackfruit is composed of rind, edible yellow flesh, procarp and, seeds which represent 8–15% of the fruit weight (Rengsutthi and Charoenrein 2011). Up to 500 seeds can be found in a single fruit, corresponding to approximately 15% of its total weight and are fairly rich in starch and protein (Suryadevara et al. 2017).

Jackfruit seeds starch has high amylose content (24–32%), high gelatinization temperature (75–85 °C), thermomechanical shear tolerance, low lipid content, acidity resistance, higher temperature and pulp viscosity, and lower pulp breakage than the gels produced by cassava and potato starches (Rengsutthi and Charoenrein 2011; Santos et al. 2009).

The production of bioplastics based exclusively on starch requires the addition of plasticizers, since these films have low machinability, that is, they are difficult to adapt to the conventional processes of package production. Plasticizers are molecules with low molecular weight and volatility, which reduce intermolecular interactions by coupling between the polymer chains and increasing their mobility, reducing the glass transition temperature, melt viscosity, modulus of elasticity, as well as fragility of films (Jerez et al. 2007; Laohakunjit and Noomhorm 2004).

Therefore, this study aimed at the production and characterization of bioplastics formed by jackfruit starch and glycerol as, although the jackfruit starch has properties compatible to produce films, no report has been found so far on the production and characterization of these materials.

Materials and methods

Seeds used for starch extraction were obtained from ripe jackfruits purchased at the street market in the city of Itapetinga, BA. Glycerol PA (Fmaia, Belo Horizonte, Brazil) was used as plasticizer.

Starch extraction

Starch extraction was carried out according to the methodology of Schoch and Maywald (1968) with modifications. Jackfruit seeds were ground in an industrial blender (Visa, 15 L, one rotation speed) in sodium bisulfite solution [0.2% (w/v) in SO₂] until the powder was very fine. The crushed mass was filtered through cotton cloth. The starch suspension obtained was decanted for 30 min at room temperature, washed several times with sodium bisulfite solution, and centrifuged (Hitachi: CF 16RX) at 900 g for 5 min at 25 °C.

After centrifugation, the supernatant was discarded and two types of solid material were obtained: the first, a light brown color mucilage, was discarded, and the second was collected as starch. The starch was dried in a tray dryer with air circulation (Solab-SL102) at a temperature of 45 °C to constant mass.

Centesimal composition of starch extracted from jackfruit seed

Moisture, ash and protein analyses were performed according to AOAC (1996). Total fiber content in the jackfruit starch sample was determined as described by AACC (1975). Quantification of starch content and total lipid content in the starch used the methodologies of Cereda et al. (2004) and Bligh and Dyer (1959), respectively.

Determination of amylose content used the simplified iodine colorimetric method, which is based on the transmission of light through a color complex that amylose forms when reacted with iodine, according to Martínez and Cuevas (1989). Absorbance reading was performed on a digital spectrophotometer (Biochrom Libra s 70) in the visible light wavelength range of 610 nm. The amylose content was obtained from the analytical curve constructed with potato amylose PA (Synth).

Starch-based bioplastic preparation

Bioplastics were prepared using the casting technique. Jackfruit starch at concentrations of 2, 3, 4, 5 and 6% w/w, and glycerol PA as a plasticizer at the concentrations of 20, 30, 40, 50 and 60 g/100 g of starch were dissolved in 200 mL of distilled water.

The suspension was heated to 95 °C under stirring on a magnetic hot plate (Fisatom 752A) for 5 min. After the heat treatment, the film-forming solution was shaken in a 40 kHz ultrasonic bath (Unique ultra cleaner, 1400) for 20 min, then poured into acrylic trays and dried in an oven with air-circulation and air renewal (Solab-SL102) at 55 °C, for 15 h. After this time, the trays with bioplastic were stored in hermetically sealed containers for 48 h with

saturated sodium bromide (NaBr) solution at 58% relative humidity.

Bioplastics analysis

Optical properties

Color determination of bioplastics was carried out with a colorimeter (Colorquest XE-Hunter Lab—USA) calibrated with a black and white backing, using standard D65 illuminant and 10° observer. The CIELAB reading system was represented by the coordinates L^* (luminosity), chromaticity coordinates a^* (− a green, + a red) and b^* (− b blue, + b yellow). The analyses were performed in three replicates, made in quintuplets, using 4 cm² film samples.

In the determination of the total color difference, the means of L^* , a^* and b^* standards were analyzed using Eq. (1):

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

where, ΔE is the difference between each color parameter of the treatments in relation to the black and white backing.

Opacity was also calculated on the same colorimeter using Eq. (2):

$$Y = \frac{Y_p}{Y_b} \times 100 \quad (2)$$

where, Y = Opacity (%); Y_p = Opacity of the sample placed on the black backing; Y_b = Opacity of the sample placed on the white backing.

Saturation was determined by Eq. (3):

$$C = \sqrt{(a^*)^2 + (b^*)^2} \quad (3)$$

Tonality was obtained by Eq. (4):

$$H = ATang\left(\frac{b^*}{a^*}\right) \quad (4)$$

Thickness

Thickness of bioplastics was measured using a precision micrometer (Kit B, Pantec). In each film sample, three measurements were performed, comprising both ends and a center point. The final thickness of each sample was considered as the mean of the measurements.

Mechanical properties

The mechanical properties were evaluated by tensile testing using a CT3 tester (Brookfield, USA), with a 25-kg load cell coupled with TA-DAGA Dual Grip Assembly

according to the methodology described by ASTM standard method D882-97 (ASTM 2012), with modifications. To perform the tensile test, test specimens were used with the size recommended by the ASTM standard for testing polymer films, and dimensions were adjusted for the size of the equipment.

The specimens were 100 mm long and 25 mm wide at the ends. Six specimens were analyzed for each treatment. The film portion (test specimen) tested was 50 mm in length and 14 mm in width. This reduction in thickness is recommended for tensile tests of various materials. The specimens were strained at a constant rate of 0.4 mm s^{−1} and 100% deformation until rupture. The parameters evaluated were: Young's modulus, Maximum force (N) and percent elongation (%).

The (%) elongation was determined by Eq. (5).

$$A(\%) = \frac{L_f - L_o}{L_o} \times 100 \quad (5)$$

where, L_f = Final sample length (mm); L_o = Initial sample length (mm).

The tensile strength was determined by Eq. (6).

$$T = \frac{F}{S} \quad (6)$$

where, F = Maximum ultimate breaking force (N); S = Cross-sectional area (m²).

Solubility in water

Solubility was determined as proposed by Gontard et al. (1992). Initially, 2 cm diameter film samples were incubated in a drying and sterilization oven (Tecnal-TE-393/I) at 105 °C, for 24 h. Then, the samples were weighed (w_i) and incubated in 50.0 mL of distilled water at 175 rpm in a rotary shaker (Quimis), at 25 °C, for 24 h. Following, the samples were removed from the water and the dry mass (w_f) was determined under the same described conditions to obtain the initial dry mass. The solubility in water was expressed as a percentage of solubilized material, calculated from the results in triplicate, Eq. (7).

$$S = \frac{w_i - w_f}{w_i} \times 100 \quad (7)$$

where, w_i = initial mass (g); w_f = final mass (g).

Water vapor permeability

Water vapor permeability was determined gravimetrically according to ASTM (2012) procedure. Disc-shaped films with 4.5 cm in diameter were placed in a permeation cell containing silica gel and formed a membrane to ensure that moisture diffusion occurs only through the films. The permeation cell was placed inside a desiccator containing

distilled water, in an air-conditioned room at 22 °C. The permeation cell was weighed on analytical balance (Scientech, As 210), 0.0001 g precision, every 24 h, for 7 consecutive days. The permeability was calculated by Eq. (8).

$$PVA = \frac{G * V}{A * T * (P_1 - P_2)} \quad (8)$$

where, *WVP* is the permeability to water vapor (g m/day m²); *G* is the mass gain (g) of the permeation cell over 24 h; *V* is the mean film thickness (m); *A* is the permeation area (m²) of the film; *T* is the time (s) and (*P*₁ – *P*₂) is the vapor pressure gradient (Pa) between the film surfaces (0.4297 × 10⁴ Pa). All tests were performed in triplicate.

Morphology and structure of bioplastics

The morphology of the bioplastic samples was assessed using scanning electron microscope (Leo 1430 VP, Germany). Two small pieces of film were fixed, one in a perpendicular position and the other in a horizontal position, on the aluminum sample holder. Then the samples were gold sputtered in a metallizer (Balzers FDU 010) for 3 min, followed by scanning electron microscope analysis. SEM images were produced with magnification of 8000 times. The films selected for analysis were those containing 4 and 12 g of starch, at the concentrations of 30 and 60% of glycerol: these values were selected because they were the minimum and maximum values of each variable that allowed the formation of non-brittle bioplastics. The images were recorded at an acceleration voltage of 20 kV.

Calculation of the free energy of the hydrophobic interaction

The free energy of the hydrophobic interaction of the films was assessed by measuring contact angles using a goniometer Kruss model FM40 Easy Drop operated in ambient air and temperature (24 °C), reducing at maximum the ambient light so as not to interfere with angle reading.

Film samples of 2 × 1 cm were fixed in glass slides with a double-sided adhesive tape. The contact angles were measured with 3 test liquids: distilled water, formamide and alpha-bromonaphthalene. A 2 µL sessile droplet was dispensed onto the surface of each sample. The image of the droplet was captured by a camera coupled to the computer, and the contact angle was calculated by the average of the measurement over 10 s, with an angle value being given at each second. The analyses were performed in duplicate.

The free energy of the hydrophobic interaction ΔG_{sas}^{TOT} between the molecules of the surface(s) immersed in water

(*W*) was calculated by summing the free energy of the interaction of the polar and nonpolar components, ΔG_{sas}^{LW} and ΔG_{sas}^{AB} , respectively (Eq. 9) (Van Oss and Giese 1995).

$$\Delta G_{sas}^{tot} = \Delta G_{sas}^{LW} + \Delta G_{sas}^{AB} \quad (9)$$

Experimental design

The experiment was arranged in a complete 5 × 5 factorial design with 5 starch concentrations (2, 3, 4, 5 and 6% w/w) and 5 plasticizer concentrations (20, 30, 40, 50 and 60% g/100 g of starch). The dependent variables evaluated included thickness, solubility, *WVP*, mechanical properties and optical properties. These dependent variables were individually expressed as a function of the independent variables using the following polynomial Eq. (10):

$$Y = \beta_0 + \sum \beta_i X_i + \sum \beta_{ii} X_i^2 + \sum \beta_{ij} X_i X_j \quad (10)$$

The experiments were performed randomly in three replicates and all necessary statistical analyses were carried out with the statistical software Statistical Analysis System[®] version 9.0, RSREG procedure (SAS Institute Inc., Cary, NC, USA), license by the Federal University of Viçosa.

Results and discussion

Centesimal composition of jackfruit seed starch

The centesimal composition analysis detected the presence of 1.17% ± 0.03 of total protein, 0.3% ± 0.01 of lipids, 0.15% ± 0.02 of fibers, 0.21% ± 0.03 of ash, 7.16% ± 0.04 of moisture and 30.08% ± 0.1 of amylose. In the current study, it is important to consider the amounts of ash, lipids, and amylose found since these are the components that influenced the formation of bioplastics.

The percentage of ash was low as indicated by low concentrations of minerals in the sample. Low concentrations of minerals favor film formation. Large concentrations of minerals may hamper the formation of bioplastics due to a possible interaction between these compounds with amylose, amylopectin and plasticizer.

The lipid content found in the jackfruit seed starch was low (0.3%). High lipid content in starch may cause the fixation of the color of the gel and consequently interfere in the color of the bioplastics and cause alterations of aroma and formation of complexes. In addition, lipids may negatively influence the swelling of the starch granule, change the gelatinization temperature, and limit amylose retrogradation, giving rise to brittle bioplastics (Singh and Nath 2013).

In this study, 30.08% of the amylose was found in the starch, which can be considered high amylose content. The amylose content in starch is an important characteristic for bioplastics production as it is responsible for gelatinization and retrogradation, which are required during film formation. Amylose is responsible for hydrogen bonding between hydroxyl groups of polymers forming junction zones between molecules and leading to film formation (Shimazu et al. 2007). Chemical, physical and functional properties of edible films and coatings depend on the amylose and amylopectin ratio (Xie et al. 2012). Joshi et al. (2013) noted that compared to corn and potato starches, lentil starch (30% amylose) possesses a strong gel-forming tendency at a relatively low concentration. Whatever the botanical origin, starch exhibits several disadvantages such as strong hydrophilic character (water sensitivity), which make it unsatisfactory for some applications.

Bioplastics characterization

Thickness

Thickness of bioplastics made with different concentrations of starch and glycerol ranged from 0.099 to 0.1599 mm. A linear effect of the starch on the thickness was found, in which thickness increased with increasing starch concentration (Eq. 11). The increase in starch concentration is associated with higher concentrations of amylose and amylopectin which results in higher solids content in the film-forming solution and, consequently, the formation of a more viscous paste giving rise to thicker films. Similar behavior was reported for bioplastics by Zavareze et al. (2012). These authors reported that the film made with 3% oxidised potato starch had thickness of 0.073 mm and 5% native potato starch had thickness of 0.168 mm. According to López and García (2012) the comparison of film thickness with those reported in the literature for hydrocolloid-based films is difficult since this property depends on the casting relation, as data rarely mentioned.

$$Esp = 0.0699 + 0.0075X_1 \quad (11)$$

where, *Esp* is the film thickness in mm and X_1 is the starch concentration in % w/w.

Morphology and structure of bioplastics

Morphology and structure were analyzed only for bioplastics made with 2 and 3% starch with 30 and 60% glycerol. The morphology of the starch-based bioplastic of jackfruit seed plasticized with glycerol is shown in Fig. 1a, b.

SEM images shows that the film surfaces exposed to air are rough with some grooves.

The micrographs show some intact starch granules, which means that the starch was not fully gelatinized during the film forming process. Analyses of bioplastics cross sections reveal that the films have irregular structure, with ridges and grooves. The cross-sectioning of the films also showed the presence of non-gelatinized starch granules. The occurrence of grooves may be explained by the presence of microbubbles formed during the gelatinization process, which was also verified in the study of Wu et al. (2009).

In addition, cross-sectional images reveal phase separation due to empty spaces inside the polymer matrix. These spaces may be formed by the volatilization of the plasticizer under the high vacuum of SEM. It is important to emphasize that starch gelatinization process occurs in a temperature range. This was resulted from gelatinization kinetic of each starch granule. It is possible that in a starch mass there are non-gelatinated granules even though the ideal conditions of this process have been used. Another factor that may influence to jackfruit starch no-gelatinized granules in the film is its high gelatinization temperature (75–85 °C), displaying a loss of molecular structure in the granules of 40–86%, respectively. This show that even above the gelatinization temperature 14% of jackfruit starch granules did not got gelatinized. Singh et al. (2009) studied the effect of iodine on the pasting properties of kidney bean starch. They reported that the swelling and gelatinization of starch was retarded by presence of glycerol.

The presence of granules with superstructure in starch (Fig. 1) don't indicate that they are intact/native. The granular structure is maintained even if the granules had lost the birefringence. According to Debet and Gidley (2007), starch dissolution is incomplete since amylopectin-rich fractions may remain insoluble and undamaged. In this case, as the starch has 70% amylopectin, this molecule can be responsible for insoluble material points in the film. Similar result was found by Garcia-Hernandez et al. (2017) for aqueous corn starch dispersion (5% w/w), with glycerol added as plasticizer (1.5% w/w).

Evaluation of the free energy of the hydrophobic interaction

The bioplastics produced had different surfaces on each of their sides. The surface in contact with the acrylic tray is highly glossy and smooth, while the interface exposed to the air is rough and opaque. The hydrophobicity analysis was performed only for the rough surface because, in case

Fig. 1 Biopolymers with 2% starch and 30% Glycerol, **a** image of the rough surface of the biopolymer with 8000× increase; The arrows are indicating the presence of non-gelatinized starch granules; **b** image

of the cross section of the biopolymer with 8000× increase; The arrow indicates the presence of grooves in the biopolymer

of bioplastics application, this is the surface that will be in direct contact with the food.

Analyzing the global free energy ΔG_{sas}^{TOT} (mJ m^{-1}) (Table 1), it found that the bioplastics made of starch and glycerol had hydrophilic behavior. The bioplastics with 6% starch and 40% glycerol were the most hydrophilic ($\Delta G_{sas}^{TOT} = 41.35 \text{ mJ m}^{-1}$). This result is explained by the high hydrophilicity of the starch, due amylose concentration ($> 30\%$) and glycerol. So these bioplastics have a high number of hydroxyl groups. According to Awadhiya et al. (2017) due the large difference in electro negativities of hydrogen and oxygen, the $-\text{OH}$ group becomes highly polar. This polarity gives the compound a strongly hydrophilic nature. Similar results were obtained by Faradilla et al. (2017) working with film produced from banana pseudo-stem nanocellulose.

Color analysis

Color parameters of bioplastics were influenced by the variation in the starch concentrations of the film formulations. The different concentrations of glycerol caused no changes. There was a decrease in the color of the bioplastics, observed for the parameters of tonality (H) and saturation (C) with the increase in the starch concentration. The variation in the film color parameters with the increase in the starch concentration may be associated with the centesimal composition of the starch. It is known that among the film constituents, lipids are the compounds that interfere with color, and the increase in the starch concentration to make the film results in an increase in the concentration of lipids. These lipid particles scatter visible light through the film (Yoshida and Antunes 2009).

For the opacity (Y) and the color difference properties it was verified an increase of their values with the increase in

Table 1 Energy free of hydrophobic interactions of plasticized biopolymers with glycerol

Starch	Glycerol	ΔG_{sas}^{TOT}
2	30	24.442
2	40	− 2.876
2	50	28.849
2	60	10.325
3	30	16.230
3	40	27.145
3	50	25.399
3	60	14.745
4	30	36.449
4	40	21.842
4	50	31.376
4	60	15.301
5	30	39.295
5	40	39.849
5	50	35.956
5	60	5.805
6	30	32.584
6	40	41.359
6	50	34.982
6	60	30.853

the starch concentration (Eqs. 12–15). According to Basiak et al. (2017) these properties are dependent on both starch origin (amylose/amylopectin ratio, size and shape of starch granules) and thickness. Matrices which contain more amylose are thicker and thus more opaque. In the present study this result is associated with the increase in amylose amount which is directly proportional to starch concentration in the film. According to Zavareze et al. (2012) the film opacity is a critical property if the film is used as a food surface coating. Transparent films are characterized by low values of opacity. In this study, the obtained opacity

values showed that films with higher jackfruit starch content were less transparent.

$$H = -1.0719 - 0.0593X_1 + 0.0025X_1^2 \quad (12)$$

$$C = -1.8200 + 0.6000X_1 + 0.0299X_1^2 \quad (13)$$

$$\Delta E = 53.4600 - 0.7200X_1 + 0.0310X_1^2 \quad (14)$$

$$Y = 13.2900 + 0.4490X_1 + 0.0208X_1^2 \quad (15)$$

where, H is the Tonality, C is the saturation, ΔE is color difference, Y is the opacity and X_1 is the starch concentration.

Solubility

The results for solubility of the bioplastics ranged from 16.42 to 23.26%. There was a continuous increase in solubility with increasing starch concentration in the film-forming solution, while the glycerol concentration had no effect on the solubility of the films (Eq. 16). This result can be explained by the higher concentrations of starch compared to the plasticizer used to produce the bioplastics. The glycerol molecule has only 3 free hydroxyls, while the starch molecule has several, thus, some hydroxyls in the starch are still available to interact with water making the bioplastic more soluble.

$$S = 12.99 + 0.856X_1 \quad (16)$$

where, S is solubility and X_1 is the starch concentration.

Water vapor permeability: WVP

The highest water vapor permeability was found for bioplastics made up of 6% starch and 60% glycerol (0.001374 g m/day m²) and the lowest WVP was for bioplastics with 2% starch and 30% glycerol (0.000307 g m/day m²). The influence of the concentration of starch and glycerol was observed by means of multiple regression analysis. Thus, as the concentration of glycerol and starch increases, the increase in WVP occurs. Equation (17) presents the statistical model that best fit WVP.

$$WVP = -0.00036 + 0.0001X_1 + 0.000085X_2 \quad (17)$$

where, X_1 is the starch concentration and X_2 is the glycerol concentration.

There was influence of the starch and glycerol concentrations on the permeability of the films produced, with the results showing an increase in WVP with the increase in the starch and glycerol concentrations (Fig. 2). Adsorption, diffusion and desorption are the main mechanisms involved in the transfer of water molecules through the starch films. These mechanisms are affected by the microstructure as determined by chemical composition,

Fig. 2 Water vapor permeability (WVP) of biopolymers plasticized with glycerol

crystallinity and plasticizer (Garcia-Hernandez et al. 2017). Therefore, the observed increase in WVP could be attributed to the hydrophilicity of the bioplastics constituents. In addition, the plasticizer interacts with the starch chains, resulting in a material with greater mobility, which increases the permeability of water through the bioplastic. According to López and García (2012), glycerol interferes with polymeric chain association decreasing the rigidity of the network; thus a less ordered and compact film structure is developed, decreasing WVP as observed in this work.

Mechanical properties

The tensile strength in the bioplastics was only affected by the plasticizer, showing a linear decreasing effect, with reduction in the tensile strength with increasing glycerol concentration (Eq. 18). The lowest tensile strength (1.65 MPa) was recorded for bioplastics with the highest glycerol concentration (60%), whereas the highest resistance (3.12 MPa) was recorded for bioplastics with 30% glycerol. When glycerol was incorporated into the polymer matrix, there was a reduction in the direct interactions resulting in a reduction in the proximity between the starch chains, thus movements of starch chains were facilitated, decreasing the bioplastics tensile strength. Tensile strength values were within the range of those recorded by López and García (2012) and Basiak et al. (2017) for ahipa and cassava and weath and cassava, respectively, starch films plasticized with a similar concentration of glycerol with those used in the present work.

$$Ts = 4.6082 - 0.0493X_2 \quad (18)$$

where, T_s is the tensile strength and X_2 is the glycerol concentration.

In the determination of the percentage of elongation of the plasticized bioplastics with glycerol, the influence of starch and glycerol was evaluated by regression analysis. By Eq. (19) the percentage of elongation of the biopolymers was determined.

$$\text{Elongation}(\%) = 29.5500 + 5.3200X_1 - 0.5280X_2 - 0.3181X_1^2 \quad (19)$$

where, X_1 is the starch concentration and X_2 is the glycerol concentration.

The percent elongation of the bioplastics was influenced by both the starch and glycerol. The percent elongation increased with increasing starch concentration, but this increase was observed up to 5% of starch, while there was a decrease in this property for the bioplastic containing the concentration of 6% starch. On the effect of glycerol, this study found that the lower the concentration, the greater the elongation of the bioplastics (Fig. 3).

The film stiffness (Young's Modulus) was influenced by the concentrations of starch and glycerol and the interaction between them (Eq. 20 and Fig. 4). The higher the starch concentration and the lower the plasticizer concentration, the higher was the stiffness of the material. Ramaraj (2007) attributed the increase of Young's modulus to a filler effect promoted by the addition of starch in the blends, with the starch granules acting as reinforcement. The bioplastics produced with 20% glycerol showed an antiplasticizer effect, which was characterized by ruptures and the non-formation of a continuous matrix, and for this reason they were not described in this study. The films

Fig. 3 Elongation (%) of biopolymers plasticized with glycerol

Fig. 4 Módulo de Young of biopolymers plasticized with glycerol

obtained in this study were stiffer than corn and potato starch films studied by López and García (2012) and Basiak et al. (2017), respectively.

$$\text{Young's Modulus} = 106.87 - 0.0348X_2^2 + 0.1564X_1X_2 \quad (20)$$

where, X_1 is the starch concentration and X_2 is the glycerol concentration.

From the results of Tensile strength, percent elongation and Young's Modulus can be verified that the jackfruit starch and glycerol provided a film with good mechanical properties. This fact is due to the formation of inter-molecular hydrogen bonding between OH groups of starch–glycerol. It is observed that the glycerol plasticizing effect in starch films, i.e., with increasing glycerol content, the films exhibited a decrease in tensile strength and Young's Modulus. The same behavior were obtained by Zanela et al. (2015), Thakur et al. (2017) working with cassava starch–PVA–glycerol and pean starch–chitosan–glycerol film, respectively.

Conclusion

The scanning electron microscopy evidenced the presence of non-gelatinized starch granules, which may have interfered in some analyses, therefore, the heating time for biopolymer production must be increased to ensure complete gelatinization of the starch. The study found that glycerol plasticized biopolymers are hydrophobic. All the optical properties of the biopolymers were influenced by the starch concentrations. The biopolymers had a low tensile strength when compared with other materials.

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