



# Biodegradable films functionalized with *Moringa oleifera* applied in food packaging

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## Abstract

Biodegradable polymers are a suitable alternative for replacing traditional food packaging with environmental concerns. Poly(butylene adipate-*co*-terephthalate) (PBAT) is a synthetic biodegradable polymer with high flexibility and a high potential for functionalization, aiming at bactericidal, antimicrobial, or antifungal properties. In this work, the casting method was used to prepare PBAT films containing *Moringa oleifera* (MO) seed powder. The MO was added in different contents of 0, 1, 3, 5, and 10% (wt) to functionalize the film properties and its efficiency as strawberry packaging. The PBAT films containing 1% (wt) of MO were the most suitable for packaging applications, considering the mechanical properties and thermal properties. MO did not present significant interactions with the PBAT matrix and reduced the PBAT crystallinity, leading to a decrease in gas and water vapor permeabilities. The PBAT-1% MO films showed good performance as biodegradable packaging for strawberry storage, prolonging their storage time and reducing their vulnerability to fungal attack. Besides, the MO decreased the fungal contamination of strawberries when compared to those stored in neat PBAT. The developed films performance suggests that the PBAT/MO films have good potential to be used as active food packaging.

**Keywords** Packaging · *Moringa oleifera* · Strawberry · Active films · PBAT

## Introduction

Packaging plays a fundamental role in the storage, transportation, and maintenance of food quality. Fresh foods, such as fruits and vegetables, are known for their short shelf life, resulting in high losses in relatively short times (~ 10 days) [1]. Among the primary packaging used by the food industry, commodity polymers are mainly used, with a production of 360 million tons worldwide every year [2]. The basic

polymers used for packaging are polyethylene, polypropylene, polyvinyl chloride, polystyrene, and polyethylene terephthalate. Despite being low-density and low-cost materials, these polymers present significant ecological issues for their disposal due to their high degradation time [3]. As an alternative to the top plastic generation with environmental problems in the packaging sector, biodegradable polymers have proven to be good alternatives in replacing the materials currently used [4, 5].

Biodegradable polymers have been studied as food packaging and coatings, as they have good mechanical and thermal properties and are non-toxic. As viable choices to produce the films, poly(butylene adipate-*co*-terephthalate) (PBAT) is a synthetic biodegradable polymer with high flexibility and a high potential for application in food packaging, as cited in the literature [6]. Due to differences in chemical structure, crystallinity, and barrier properties, in general, biodegradable films are functionalized, aiming to add function and improve performance [7, 8].

Several active agents are added among active or functional packaging materials, aiming at bactericidal, antimicrobial, or antifungal properties [1]. Among the primary

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materials used, TiO<sub>2</sub>, Ag, and Au nanoparticles are the main antimicrobial agents. However, various natural fibers have been used to prepare PBAT compounds, such as manga wastes, essential oregano oil, and natural fibers from the Amazon rainforest [9–11]. *Moringa oleifera* seed powder has stood out in recent years [12–14]. This material contains high-quality protein (~52%) and essential amino acids, which confers antimicrobial properties. Also, the seeds are rich in oils and glycosylates [14, 15]. The bactericidal effects of these proteins, contained in the powder, were confirmed for several microorganisms [16–19].

In this work, the PBAT/*M. oleifera* (MO) seed powder composites with different MO contents were prepared by film extension (casting) method for application in food packing for strawberry. Morphology, chemical composition, thermal stability, and crystallinity evaluated the MO properties. Various techniques characterized the films, including mechanical tests, SEM, FT-Raman, TGA, DSC, XRD, oxygen and water vapor permeability, and their strawberry application performance. The overarching aims of this research were twofold: (i) examine the effect of MO content on PBAT/*Moringa* composites, and (ii) to evaluate the performance of the developed composites as food packaging.

## Experimental

### Materials

Poly (butylene adipate-*co*-terephthalate) (PBAT) ( $M_w$  66,500 g/mol) was purchased from BASF (São Paulo, Brazil) under the trade name Ecoflex. *M. oleifera* seeds were purchased from a local producer (Casa Nova-Bahia, Brazil). Chloroform (1.48 g/cm<sup>3</sup> density at 25 °C) was purchased from Synth (Diadema-SP, Brazil).

### Preparation of *M. oleifera* powder

The seeds were dried for 24 h at 60 °C. The dried seeds were peeled and reduced to powder using a home-made processor (Mondial Power 21,500 W) for 10 min. A magnetic sieve separated the resulting powder for 10 min, and the opening, selected for separation of the powder size, was mesh #200 (75 μm). The sample was named MO.

### Preparation of composite films by extension method

PBAT was first dried at 50 °C for 24 h before use. Then, 20 g of PBAT was dissolved in 100 mL of chloroform with constant magnetic stirring. The polymeric solution was then applied to a glass plate (13 × 18 cm) and extended in film form using a wire extender TKB Erichsen (200 μm). The

plates were air-dried for 1 min, in order to partial evaporation of the solvent (flash-off). The plates were then immersed in demineralized water, in polyethylene trays of 24 × 32 cm (internal dimensions) to perform a coagulation bath. Films were detached from the glass plate's surface (peel-off effect) and removed from the solution to dry. For composites, MO powder was incorporated after the solubilization of PBAT in different contents of 1, 3, 5, and 10% (wt). Figure 1 shows the methodology schematically.

## Characterization

### Optical microscopy and scanning electron microscopy

The MO power was evaluated by optical microscopy (ZEISS microscope, model AXIO Scope A1), with 50-fold magnification. A granulometric analysis measured the particles' sizes. An MEV FEI Quanta 250 scanning electron microscope examined the *Moringa* powder's morphological characteristics and the developed films. The samples were previously covered with gold by the sputtering technique (Leica ACE200) with a 20 nm gold deposition on the samples' surface.

### Fourier transform infrared spectroscopy (FTIR)

An equipment Frontier 94,942 (PerkinElmer, USA) collected the FTIR data, in the range of 400–4000 cm<sup>-1</sup>, with 64 scans and a 4 cm<sup>-1</sup> resolution, equipped with an attenuated total reflectance (ATR) accessory with diamond. Origin 8 software processed the data.

### Fourier transform Raman spectroscopy (FT-Raman)

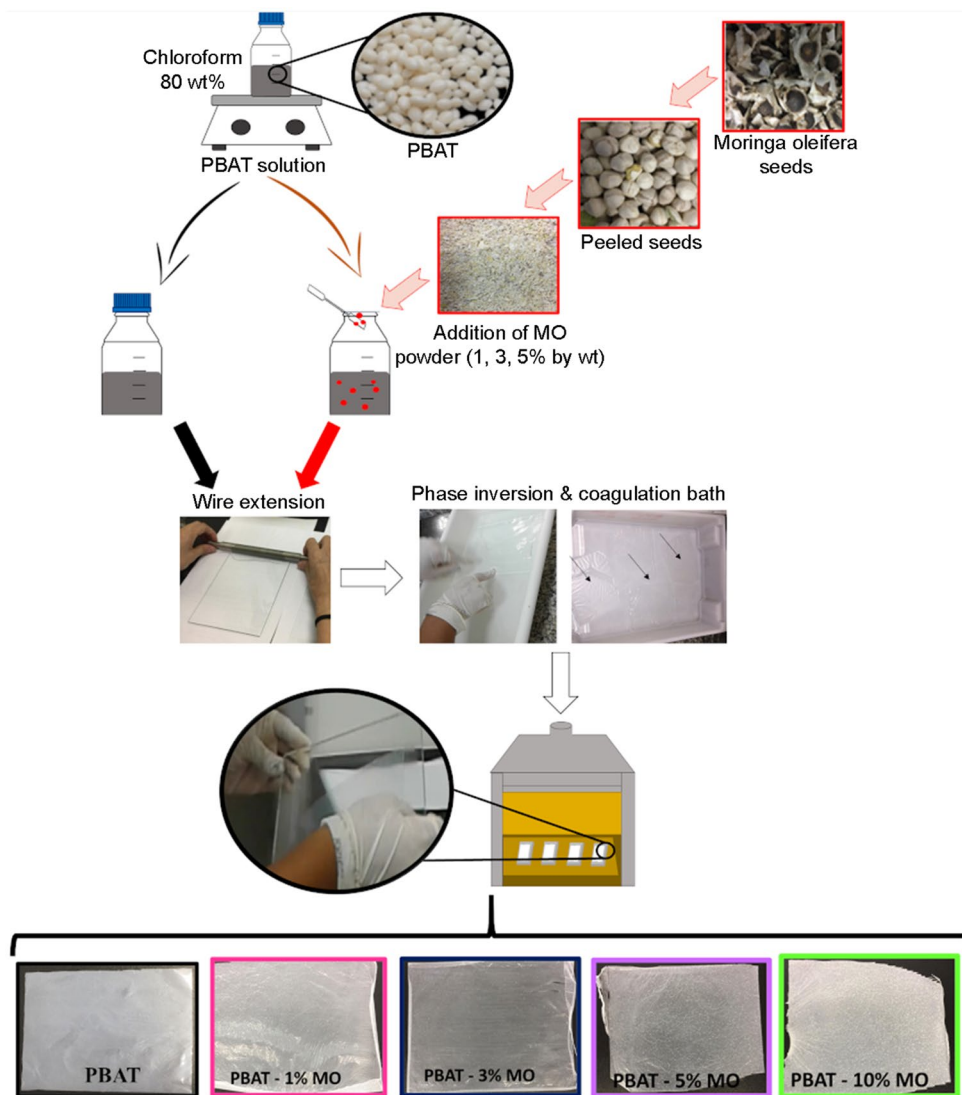
The samples were analyzed using an FT-Raman equipment (MultiRaman, Bruker Optics) equipped with a 1064 nm wavelength and a 150 W power laser. The data acquisition parameters were: 600–4000 cm<sup>-1</sup>, 32 scans, and 4 cm<sup>-1</sup> spectral resolution.

### X-ray diffraction (XRD)

A D8 Focus diffractometer (Bruker AXS-Karlsruhe, Germany) collected the data using monochromatic CuK<sub>α</sub>1 radiation  $\lambda = 1.54056 \text{ \AA}$ , operating at 40 kV and 40 mA, with a step width of 0.015° and counting time of 100 s at each 0.5°, from 2θ of 10°–50°. The crystallinity index was calculated by Eq. (1) [20]:

$$CI = \frac{(I_{200} - I_{am})}{I_{200}} \quad (1)$$

**Fig. 1** Flow diagram representative of the PBAT composites preparation



$I_{200}$  is the peak of highest intensity ( $2\theta \sim 22.5$ ), and  $I_{am}$  is the peak lowest intensity ( $2\theta \sim 18$ ).

### Thermogravimetric analysis (TGA)

The thermogravimetric analysis was conducted on an STA 6000 equipment (PerkinElmer, USA), using alumina pans. The samples were heated from 30 to 600 °C at a rate of 10 °C/min under nitrogen atmosphere with a flow rate of 20 mL/min.

### Mechanical tests

The tensile tests were investigated by an equipment Instron 3367 (Norwood, USA) at room temperature by the standard ASTM D638-14, with a load cell of 50 N and a test speed of 50 mm/min. The compositions were tested in quintuplicate.

### Differential scanning calorimetry (DSC)

A DSC Q-series (TA Instruments) (New Castle, Delaware, USA) collected the DSC data under the nitrogen atmosphere (50 mm/min). The samples were heated to 190 °C, cooled to – 60 °C and, then heated to 200 °C. Equation (2) describes the calculation of the degree of crystallinity ( $X_c$ ), where  $\Delta H_m$  is the experimental fusion enthalpy, and  $\Delta H_{100\%}$  is the theoretical enthalpy of PBAT (114 J/g).

$$X_c(\%) = \frac{\Delta H_m}{\Delta H_{100\%}} \times 100 \quad (2)$$

## Oxygen and water vapor permeability

The oxygen transmission rate ( $O_2TR$ ) was determined according to the ASTM D 3985-17 at  $23 \pm 0.5$  °C in a coulometric sensor equipment (Mocon, Oxtran model ST, IL, USA). The film outer side was placed in contact with the permanent gas (100%  $O_2$ ). The readings were corrected to 1 atm of partial pressure gradient of permanent gas and oxygen partial pressure gradient between the two surfaces of film. This gradient corresponds to the driving force for oxygen permeation through the film.

Once  $O_2TR$  was determined, the oxygen permeability coefficient was calculated by Eq. (3):

$$O_2P = \frac{O_2TR \cdot L}{P(1)} \quad (3)$$

where,  $O_2P$  is the oxygen permeability coefficient ( $mL$  (CNTP)  $mm^{-2} day^{-1} atm^{-1}$ ),  $O_2TR$  is the oxygen transmission rate ( $mL$  (CNTP)  $m^{-2} day^{-1}$ ),  $L$  is the mean film thickness ( $\mu m$ ), and  $P$  is the oxygen partial pressure in the gas chamber permeating the diffusion cell (1 atm). The partial pressure of  $O_2$  in the carrier gas chamber ( $N_2 + H_2$ ) is considered null.

The water vapor transmission rate (WVTR) followed the ASTM E 96/E 96M-05 methods at  $25 \pm 0.5$  °C, and anhydrous calcium chloride (0% RH) filled the cells. The cells were covered with the films, sealed, and placed in a climatic chamber (Votsch, VC 0063 model, German) at  $75 \pm 2\%$  RH. Once the WVTR was determined, Eq. (4) determined the water vapor permeability coefficient.

$$WVP = \frac{WVTR \cdot L}{PWVS(RH1 - RH2)} \quad (4)$$

where, WVP is the water vapor permeability coefficient ( $g$  water  $mm^{-2} day^{-1} mmHg^{-1}$ ), WVTR is the water vapor transmission rate through a film ( $g$  water  $m^{-2} day^{-1}$ ),  $L$  is the mean film thickness ( $\mu m$ ), PWVS is the partial water vapor saturation pressure at the test temperature ( $mmHg$ ). RH1 is the chamber relative humidity (0.75), and RH2 is the relative humidity inside the capsule with desiccant (0% RH).

## Films performance as packaging for strawberries

Strawberries were purchased from a local farm (Santo André-SP, Brazil) and immediately treated with sodium hypochlorite (250 ppm), and then dried at room temperature. Fruits of uniform size and free of fungal actions or physical damage were selected. The washed fruits were put in PBAT films and their composites and sealed by a manual plastic packaging sealer at a temperature of 120 °C (TECNAL STN, São Paulo, Brazil). Low density polyethylene (LDPE)

and polyvinyl chloride (PVC) films were used to compare commercial materials with the new formulation [21, 22]. A refrigerator at 4 °C stored the samples. Photographs were taken from the fruits at the beginning of the experiment, and after 3, 7, 10, and 15 days of storage [23].

## Results and discussion

### *M. oleifera* seed powder characterization

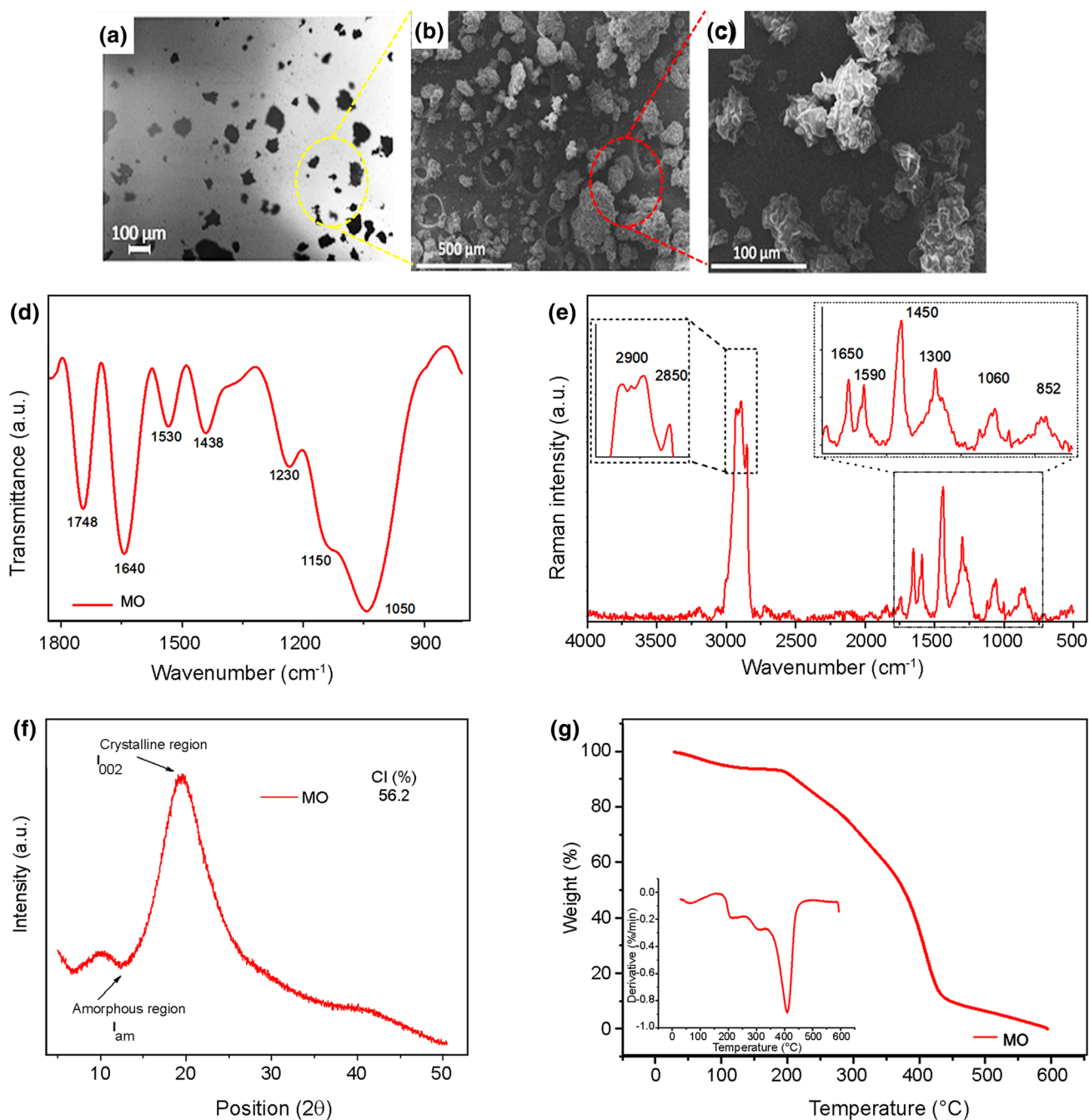
#### Granulometry and morphological analysis

The optical microscopy evaluated the morphology and regularity of the power, as shown in Fig. 2a. The particles were analyzed by the Image J software to measure the particle diameter, and the average diameter was  $40.9 \pm 9.7$   $\mu m$ . Figures 2b, c show the scanning electron micrographs of MO power. This material is heterogeneous and has a relatively porous matrix [24]. This porosity, according to Shirani et al. contributes to the efficiency of this biopolymer in removing bacteria and fungi [25].

#### FTIR and FT-Raman

Infrared spectroscopy investigated the MO powder structure in the dried state. The typical spectrum (Fig. 1S, Supplementary Material) showed peaks between 4000 and 1000  $cm^{-1}$ . The peak in the region of 3500–3200  $cm^{-1}$  indicates alcohol or phenol, a functional group predominant in the structures of proteins and fatty acids present in *M. oleifera* seeds [26]. The peak below 3400  $cm^{-1}$  indicates NH elongation, and intense peaks at 3398  $cm^{-1}$  are associated with –OH elongation [27]. Bands between 2800 and 2900  $cm^{-1}$  are associated with the extent of CH vibration, and their high intensity is also associated with the presence of long carbon chain compounds, that is, the methylene groups in lipid and cellulose molecules [28]. The presence of bands between 1800  $cm^{-1}$  and 1500  $cm^{-1}$ , observed in Fig. 2d, is related to proteins and amino acids. The peak at 1748  $cm^{-1}$  represents carboxylic groups. The band between 1669 and 1527  $cm^{-1}$  provides the stretching vibration added to the carbonyl group (C=O) [29].

*M. oleifera* active groups are mainly proteins. Under suitable conditions, these proteins can be extracted from the seed to obtain a concentrated extract, or they can also be obtained from the seed in nature through the exudation process, which occurs naturally. According to Kwaambwa and Maikokera, the organic groups of MO protein are characteristic of amide I and II [30]. The spectra showed two strong absorption bands of 1658 and 1544  $cm^{-1}$  of amides I (protein  $\alpha$ -coil helix) and II, respectively, which



**Fig. 2** **a** Optical microscopy image of the *Moringa oleifera* seed powder. **b, c** Scanning electron microscopy with different zooms of the MO sample. **d** FTIR spectrum zoom between 1800 and 800  $\text{cm}^{-1}$ . **e**

FT-Raman spectrum of MO with inserts from the 2950–2800  $\text{cm}^{-1}$  and 1700–800  $\text{cm}^{-1}$  regions. **f** XRD. **g** TGA of *M. oleifera* powder

confirmed the structure of the protein present in the *Moringa* seeds [31, 32].

Flexion vibrations between 1449 and 1338  $\text{cm}^{-1}$  represented O–H and C–N (from aromatic amines) [29]. The peaks at 1230, 1150, and 1050  $\text{cm}^{-1}$  represented acetyl groups present in the lignin structure, and C–O and C=O

elongation of ether, ester, and phenol bonds, respectively [33].

Raman spectroscopy was used as a complementary technique to FTIR to analyze the structure and functional groups of the ground *Moringa* seed (Fig. 2e). The peaks 2930, 2910, and 2850  $\text{cm}^{-1}$  were assigned to =CH<sub>2</sub> stretch. The peaks



of 1650 and 1590  $\text{cm}^{-1}$  corresponded to amide groups I and II, respectively [34]. The peaks at 1450 and 1300  $\text{cm}^{-1}$  were associated with C–NH vibrations of tertiary amides [35], while at 1060 and 852  $\text{cm}^{-1}$  they were associated with C–C=CH<sub>2</sub> stretches and the CCO– vibration, respectively.

### X-ray diffraction (XRD)

Figure 2f shows the diffractograms of MO powder. The seeds are composed of a high amount of oil, protein, and a cellulose fraction. The characteristic XRD peak at 22.5° is associated with the plane (002), and the amorphous region was verified at 12.5° [34]. Segal equation analyzed the crystallinity index (CI), and a CI value of 56% was obtained, which corroborates the literature [28].

### Thermogravimetric analysis (TGA)

Figure 2g shows the MO thermogram. The sample has three main events of weight loss: the first occurs between 30 and 130 °C and is associated with loss of water, volatiles, and low molar mass components. The second is associated with the loss of gases, such as CO<sub>2</sub> and NH<sub>3</sub>, resulting from the protein amine groups [34]. The third event occurs from 300 to 428 °C, which corresponds to the MO powder [36, 37].

### Films characterization

#### Mechanical tests

Mechanical properties are essential for food packaging since good flexibility and mechanical resistance are required to protect the food during handling, transport, and storage. Table 1 shows the mechanical properties of films. The PBAT showed stiffness values of approximately 160 MPa and  $\epsilon$  of ~125%; these values are consistent with those reported in the literature [38, 39]. The MO addition decreased the  $E$ ,  $\sigma$ , and  $\epsilon$  associated with the weak stress transformation across interphase [40]. However, there is another possibility to explain the mechanical resistance: the composite's

**Table 1** Results of the tensile test of films containing Moringa powder: elastic modulus ( $E$ ), tensile strength ( $\sigma$ ), and elongation-at-break ( $\epsilon$ )

Samples	Elastic modulus ( $E$ ) (MPa)	Tensile strength ( $\sigma$ ) (MPa)	Elongation-at-break ( $\epsilon$ ) (%)
PBAT	161.7 ± 28.1	7.7 ± 0.8	124.6 ± 23.7
PBAT-1% MO	84.2 ± 2.8	3.8 ± 1.9	78.6 ± 19.2
PBAT-3% MO	44.6 ± 3.4	1.5 ± 0.2	74.4 ± 5.8
PBAT-5% MO	43.7 ± 4.4	1.3 ± 0.5	50.7 ± 9.1
PBAT-10% MO	56.7 ± 5.9	1.3 ± 0.4	30.8 ± 7.0

preparation method. During the phase inversion process, the polymer was submerged in water, which induced the formation of pores in the films due to MO's high hydrophilicity, reducing the final material [39, 41, 42].

According to conventional standards,  $\sigma$  for packaging film must be > 3.5 MPa [43]. Thus, PBAT-1% MO is most suitable for such an application. The other compositions showed a significant decrease in mechanical properties, associated with MO's high content, leading to possible pores appearance.

### Scanning electron microscopy

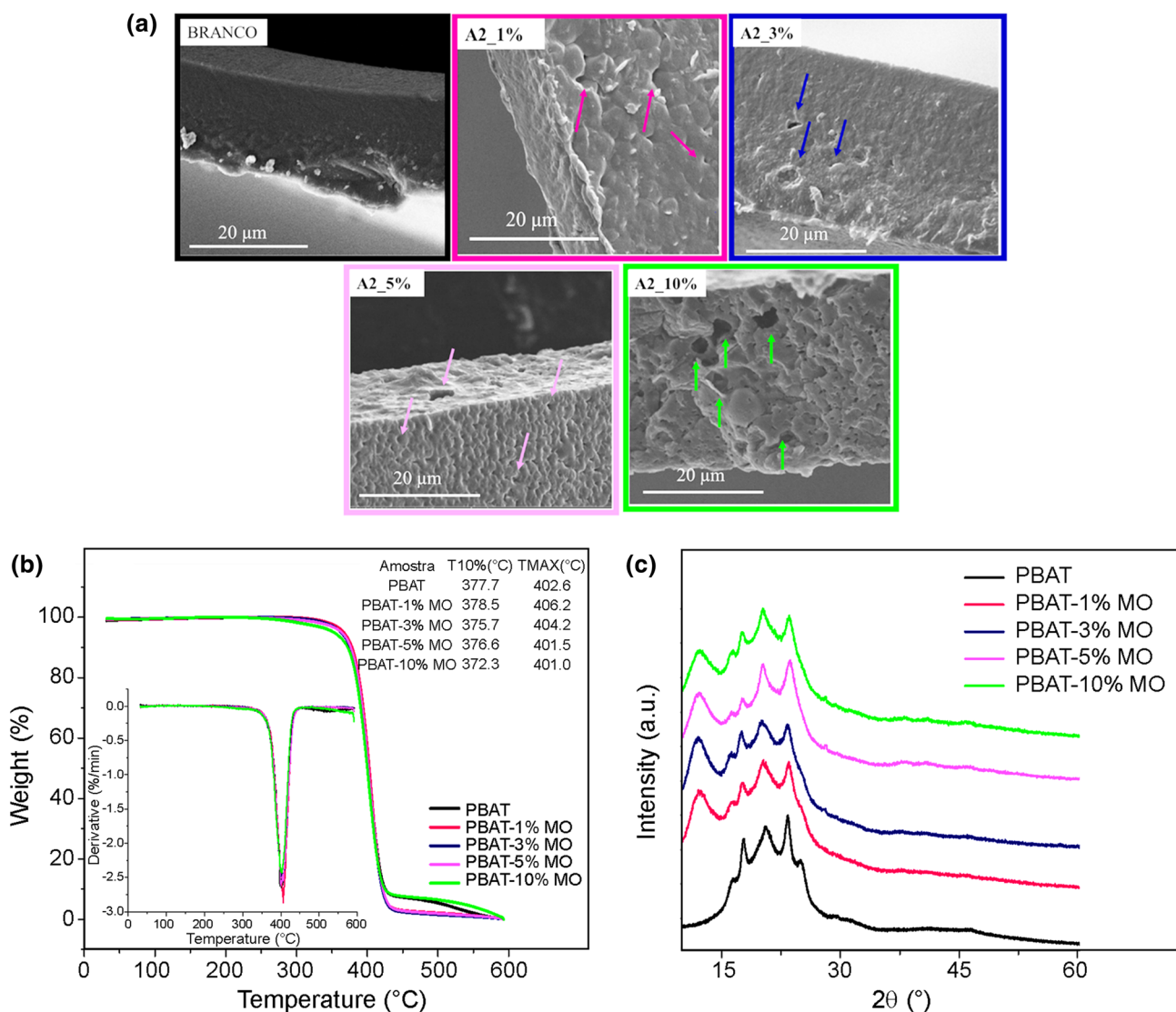
SEM images reveal information about the morphology of composites and filler dispersion. The neat PBAT showed a smooth and homogeneous surface, as presented in Fig. 3a. After the addition of MO, a porous and highly rough surface was formed. The indicative arrows in the photomicrographs indicate voids formed by the absence of a reinforcement phase. According to Moustafa et al. this behavior can indicate *M. oleifera* particles [44]. Despite the matrix being porous, Wu et al. stated that variations in oxygen or water vapor permeation occur in active packaging and positively influence food storage [45].

### Thermal properties

Figure 3b shows the TGA curves and their derivative thermogravimetric (DTG) curves of all the composites. PBAT showed a  $T_{10\%}$  of 377.7 °C and  $T_{\text{max}}$  of 402.6 °C, with a single weight-loss event. The values found are similar to those reported in literature [46]. The PBAT thermal degradation is associated with the C–C bonds cleavage present in the polymer structure [47]. After the addition of MO, no separate degradation stage occurred, which indicates that *M. oleifera* has been entirely covered by PBAT molecules [48].

Table 2 summarizes the DSC results, and Fig. 2S (Supplementary Material) shows the second heating and cooling curves. The PBAT-MO samples have higher  $T_g$  values, and PBAT-1% MO presents the high values attributed to the uniform dispersion of MO, and probably this sample shows the best adhesion/cover between PBAT and MO [13]. The *M. oleifera* restricts the mobility of polymer segments and increases the glass transition temperatures. No significant differences were observed in the melting temperature [11].

The  $T_c$  values significantly increased after the MO addition, which means that the MO facilitates PBAT crystallization, acting as a nucleating agent [49]. The slight changes observed in the  $X_c$  values are associated with a possible change in polymer crystallization kinetics. Smaller amounts of MO do not affect crystallization, while larger amounts limit the crystallite growth, generating a smaller size crystalline phase, reflecting the decrease in  $X_c$  values.



**Fig. 3** a SEM micrographs of the fractured surfaces for neat PBAT and its composites, and the arrows indicate the voids presence. b TGA and DTG curves of the neat PBAT and its composites. c X-ray diffraction patterns of the PBAT and PBAT-MO

**Table 2** DSC results of PBAT and PBAT-MO samples ( $T_g$ ,  $T_m$ ,  $\Delta H_m$ ,  $T_c$ ,  $X_c$ ), and crystallinity index (CI) calculated from XRD results; oxygen permeability coefficient ( $O_2P$ ) and water vapor permeability coefficient (WVP) of PBAT films without and with *M. oleifera*

Sample	$T_g$ (°C)	$T_m$ (°C)	$\Delta H_m$ (J/g)	$T_c$ (°C)	$X_c$ (%)
PBAT	- 43.2	124.2	11.5	68.7	10.1
PBAT-1% MO	- 34.8	125.5	13.1	78.1	11.5
PBAT-3% MO	- 35.7	124.5	10.9	76.2	9.5
PBAT-5% MO	- 36.1	124.8	10.1	78.8	8.8
PBAT-10% MO	- 39.8	122.8	8.6	79.3	7.5

Sample	$O_2P$ [mL (STP) $\mu\text{m}^{-2} \text{day}^{-1} \text{atm}^{-1}$ ]	WVP (g water $\mu\text{m}^{-2} \text{day}^{-1} \text{mmHg}^{-1}$ )
PBAT	31.1 ± 1.0	323.3 ± 26.6
PBAT-1% MO	62.9 ± 9.5	382.8 ± 9.1
PBAT-3% MO	102.3 ± 0.6	455.9 ± 4.7
PBAT-5% MO	199.8 ± 5.1	692.9 ± 24.1
PBAT-10% MO	719.5 ± 2.6	774.5 ± 13.6

**Table 3** Crystallinity index (CI) obtained from XRD patterns

Sample	Crystallinity index (%)
PBAT	9.7
PBAT-1% MO	8.2
PBAT-3% MO	9.6
PBAT-5% MO	8.5
PBAT-10% MO	7.6

### X-ray diffraction

XRD was used to examine the crystallinity of PBAT and the PBAT/MO samples (Fig. 3c). PBAT exhibits five characteristic diffraction peaks at 16.2°, 17.3°, 20.4°, 23.4°, and 25.2°, associated with the planes (011), (010), (110), (100), and (111) [50, 51]. The PBAT diffraction pattern remained unchanged after the MO addition. No transcrystalline phases were created in the system interface [50]. Small shifts were observed for the PBAT structure, emphasizing the 20.4° angle, which shifted to ~20.0°. This small variation may indicate a change in the formation of PBAT crystallites. However, a new broad peak at 12° was detected, which can be associated to the MO XRD pattern, confirming MO incorporation in the composites. Table 3 shows the crystallinity values obtained by XRD patterns.

The crystallinity differences observed between the XRD and the DSC can be associated with the test methodology. While the DSC occurs through the polymer melting and cooling, the XRD is performed on the prepared films. Since in the present study, the films were prepared by wire extension, the XRD data is closer to the real crystalline structure found in the developed films.

### Oxygen permeability and water vapor permeability

The addition of MO (Table 2) greatly influenced the O<sub>2</sub>P and WVP values. PBAT is a polymer with high O<sub>2</sub>P and WVP values due to its chemical structure and physical properties, such as low crystallinity [52, 53]. The addition of *M. oleifera* decreased the films oxygen barrier properties, which can be attributed to the films lower crystallinity, i.e., the MO reduced the films abilities to act as oxygen barriers [54]. The oxygen permeabilities increased rapidly with the powder Moringa content when the latter is over 3% (wt), resulting in blend films with weaker oxygen barrier properties [55]. The O<sub>2</sub>P is highly dependent on film structure, thickness, void volume, and arrangement of the polymer chain [56]. As previously described, the addition of Moringa resulted in low interactions between the PBAT matrix and the MO powder. Thus, the presence of pores changed the PBAT chain arrangement. Despite the increase in O<sub>2</sub>P values, it is important to note that the Moringa seed has

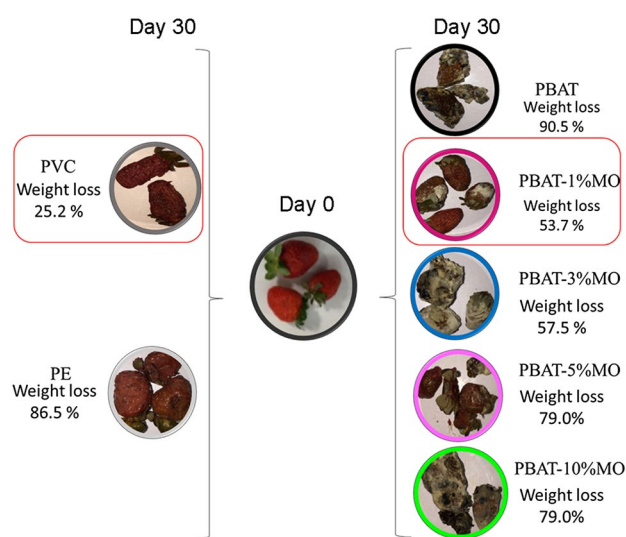
known active properties. Thus, with the balance between the OM functionality and the permeability, the developed packaging, mainly the films PBAT-1% MO, is suitable for certain foods, such as strawberries.

Table 2 also shows the WVP values of PBAT films without and with MO. The addition of MO powder increased the WVP values, which the interaction between PBAT and powder Moringa can decrease the water vapor barrier properties. The MO is a hydrophilic material that favors transfer of water molecules through the film [57]. Besides, the lower crystallinity of film favors the diffusion of water molecules since the polymer chains are less densely packed due to *M. oleifera* powder. The PBAT and PBAT-1% MO films showed very similar water vapor permeability coefficients. Furthermore, increasing the powder content increases the WVPs of the films [55].

### Films performance as packaging for strawberries

The strawberries are highly susceptible to rapid loss of water owing to respiration and transpiration. Commonly, weight loss occurs during the fruit storage because of its respiratory process, humidity transfer, and oxidation [58]. Figure 4 shows strawberries before packaging after the last test day (day 30). In Fig. 4, it is also possible to observe mass loss suffered by the fruits after 30 days. Figure 3S (Supplementary Material) shows the packaged strawberries and the visual changes observed after 0, 3, 7, 10, and 15 days.

The weight loss harms appearance of strawberry fruits, leading to shrinkage and opaque-looking skin. Fruit storage is an important parameter that controls and slows deterioration [59].

**Fig. 4** Digital images of the appearance of strawberries at days 0 and 30



The samples that showed less weight loss were PVC (25.2%) and PBAT-1% MO (53.7%). According to the literature, PVC film used as a control sample has low permeability rates to oxygen and water vapor, which justifies its small mass loss and the absence of fungi visible to the naked eye. Besides, the strawberry did not lose the water, which maintained its weight [60].

Considering the PBAT samples without and with MO, neat PBAT was the one that presented the most significant loss of fruit mass after 30 days of storage. Also, films with 3, 5, and 10% MO showed the highest amounts of visible fungi, while the sample with 1% MO was the one with the least damaged and contaminated strawberries. It can be associated with the agglomeration effect: while 1% showed good dispersion, the other contents may have resulted near of the particles to each other, which limited the release of the active agent. The presence of MO in small amounts can cause cell damage in mold and yeast, altering the synthesis

of fungal enzymes [61, 62]. Thus, morphological changes can occur and cause structural changes and molecular disorganization in fungal cells [63] (Fig. 5). As observed in the FTIR analysis, the seeds have distinct groups that show protein in the MO powder. Exudation of Moringa proteins (i.e., active compound) from the powder surface to the films results in damage to microbial cell membranes, minimizing the fungal attack on strawberries.

The biodegradable films effectively delay senescence, making the fruits more vulnerable to pathogenic infection due to loss of cellular or tissue integrity. Therefore, PBAT-1% MO films were useful as biodegradable packaging for storing sensitive fruits, such as strawberries, by prolonging their storage time and reducing their vulnerability to fungal attack. The packaging is biodegradable and is a potential substitute for the commodities currently used, and its performance is comparable to the performance of PE packaging.

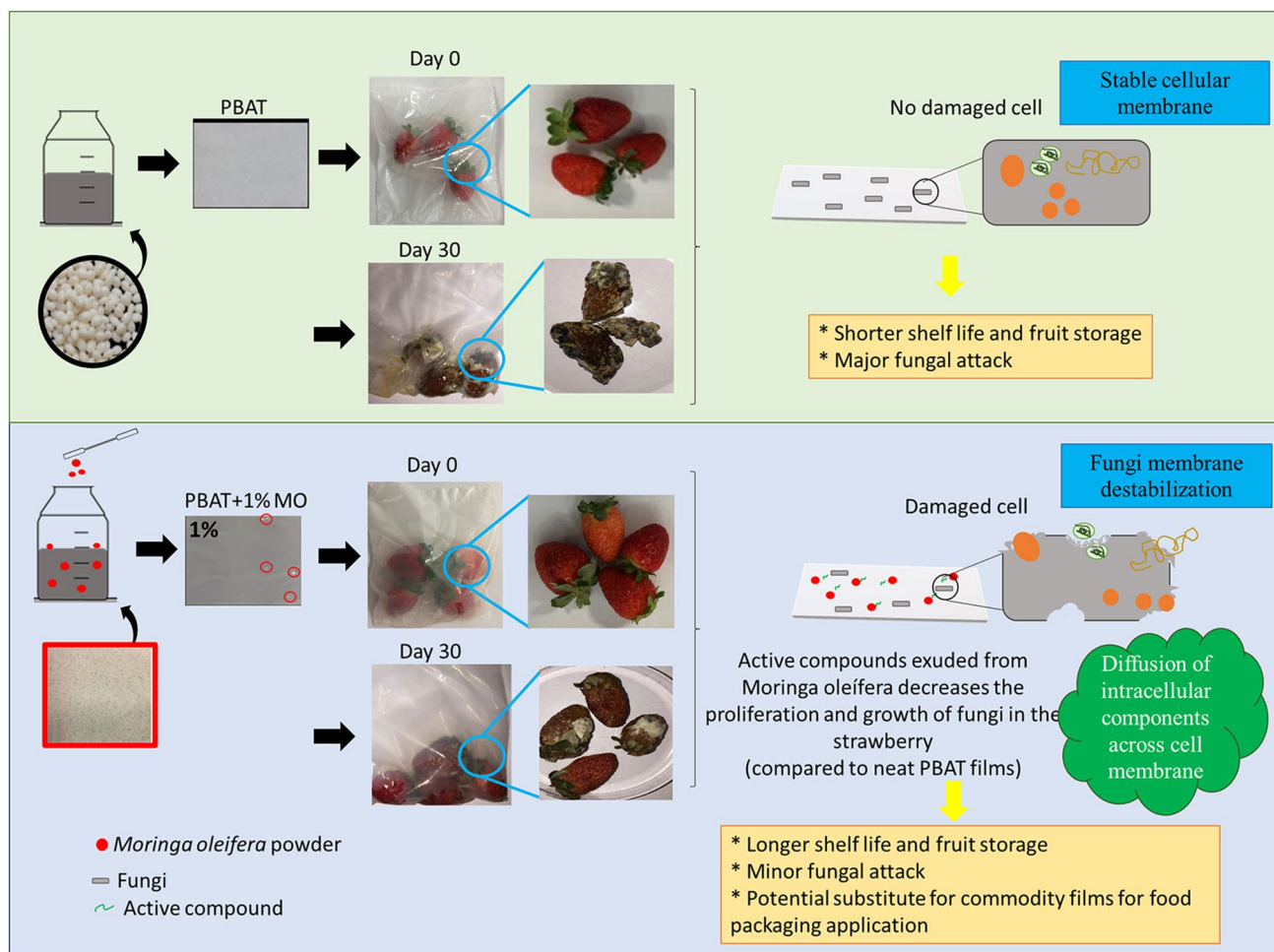


Fig. 5 Schematic representation of the addition of MO in PBAT films and its effect on the strawberry’s storage

## Conclusion

PBAT/MO films were successfully prepared using *M. oleifera* (MO) seeds in the powder form. Samples containing 1% MO showed the best results in their mechanical properties. The maximum stress values correspond to the values of international standards required for packaging applications (above 3.5 MPa). The films showed good thermal stability, only slightly decreased for samples with higher MO content. The PBAT/MO samples showed higher  $T_g$  values since the MO particles restricted mobility of polymer segments. No changes were observed on  $T_m$  values associated with the absence of chemical interaction between the MO and the PBAT. These results were confirmed by FT-Raman analysis. However, the absence of interactions can be beneficial, considering MO available active sites for subsequent interaction with pathogenic microorganisms. The reinforcement addition reduced the crystallinity of the films, changing the structural organization of PBAT polymer chains. The lower crystallinity reflected in the oxygen and water vapor permeability and the films containing *M. oleifera* showed high permeability, which increased with MO content. Possibly, due to permeability changes, the films containing MO allowed the strawberries to breathe more efficiently, which delayed their deterioration. Only the 1% MO sample showed consistent results for use in packaging. PBAT-1% MO films showed good performance as packaging for strawberry storage, prolonging their storage time, and reducing their vulnerability to fungal attack.

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## Compliance with ethical standards

**Conflict of interest** The authors declare that there are no conflicts of interest.

**Availability of data and material** The authors are willing to provide the manuscript's data, if necessary.

**Code availability** Not applicable.

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