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ORIGINAL ARTICLE

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High-pressure processing effects on the barrier properties of flexible packaging materials

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Abstract

The aim of this research was to evaluate the influence of high-pressure processing on the barrier properties of flexible packaging. LDPE/PA/LDPE, LDPE/EVOH/LDPE, PET/LDPE/PA/EVOH/PA/LDPE, PET/Al/PA/PP, and $PET_{printing}/PET_{met}/LDPE_{coex}$ packaging were filled with distilled water, processed by three conditions (600 MPa/25°C/10 min, 600 MPa/90°C/10 min, and 0.1 MPa/90°C/10 min) and evaluated when the barrier to water vapor, oxygen, and light. The different processing conditions had little effect on the water vapor barrier and did not affect the light barrier of the packaging. The biggest changes were in the oxygen barrier, increasing oxygen permeation by 1.15, 2.24, 1.65, and 13.10 times for packaging of LDPE/PA/LDPE, LDPE/EVOH/LDPE, PET/LDPE/PA/EVOH/PA/LDPE, and $PET_{printing}/PET_{met}/LDPE_{coex}$, respectively, after processing 600 MPa/90°C/10 min, these results were influenced by the synergistic effect of high-pressure and high-temperature, indicating that, depending on the process condition and the composition of the packaging materials, the barrier properties may decrease and, as a consequence, cause a reduction in the shelf life of the food.

Practical applications

The global high-pressure processed food market is growing. In addition to knowing the effects of this technology on food, it is essential to evaluate packaging materials, since, in most cases, foods are processed and marketed in the same packaging. Studies that address the impact of different processing conditions on the barrier properties of different packaging materials are essential for the best use of this technology, as they can undergo changes that can lead to a reduction in the shelf life of food, which will also depend chemical composition of food and storage conditions (time, temperature, and relative humidity).

Abbreviations: Al, aluminum foil; EVOH, ethylene vinyl alcohol; HPP, high-pressure processing; LDPE, low-density polyethylene; OTR, oxygen transmission rate; P, pressure; PA, polyamide; PATS, pressure-assisted thermal sterilization; PET, polyethylene terephthalate; PP, polypropylene; RH, relative humidity; STP, standard temperature and pressure; T, temperature; t, time; WVTR, water vapor transmission rate.

1 | INTRODUCTION

Conventional thermal processing of pasteurization and sterilization has been used for many decades to produce stable and safe food. However, these techniques are no longer considered the preferred solution, mainly due to their impact on the loss of sensory and nutritional quality of food (Bahrami, Moaddabdoost, Schimmel, Mahdi, & Williams, 2020). The same has happened with foods that contain chemical additives, mainly chemical preservatives that are rejected by consumers (Bahrami et al., 2020; Huang, Wu, Lu, Shyu, & Wang, 2017). Thus, emerging technologies for food processing have often been cited by researchers as an alternative to conventional heat treatments (Hernández-Hernández, Moreno-Vilet, & Villanueva-Rodríguez, 2019). As a result, several technologies have been driven and studied thoroughly to provide a solution to consumer demand for convenience and sensory quality (Lavilla & Gayán, 2018). In this context, the global demand for environmental preservation and food security is growing, with innovation being the key to the development of the food industry. These technologies tend to reduce water and energy consumption, playing important roles in the economic and environmental sustainability of food processing (Khan, Ahmad, Hassan, Imran, & Ahmad, 2018; Knoerzer, Buckow, Trujillo, & Juliano, 2015).

Among the different emerging food processing technologies, high-pressure processing (HPP) stands out. Currently, HPP is successfully applied on a commercial scale in many food products, such as: fruit juices, seafood, meat, and dairy products; vegetable products, ready-to-eat foods, salads, and sauces (Misra et al., 2017). HPP inactivates vegetative bacteria, yeasts, and fungi using pressures up to 600 MPa at room temperature and can inactivate spores when combined with high-temperature (pressure-assisted thermal sterilization - PATS). HPP retains much of the sensory and nutritional quality of a liquid or solid product and its effect on enzymes is variable, as highlighted by Jermann, Koutchma, Margas, Leadley, and Ros-Polski (2015). The HPP is governed by the *Le Chatelier* principle, that is, reactions or phase transitions associated with a decrease in volume are favored (Barba, Shiferaw, Buckow, Knorr, & Orlien, 2015; Misra et al., 2017; Norton & Sun, 2008; de Oliveira, Ramos, Ramos, Piccoli, & Cristianini, 2015). Low molecular weight molecules, such as aromatics compounds, vitamins and minerals, are rarely affected due to the low compressibility of covalent bonds. On the contrary, macromolecules, such as proteins and carbohydrates, may have their structure modified during processing (Barba et al., 2015).

According to Barba et al. (2015) three processing parameters are important in HPP: temperature (T), pressure (P), and time (t) and when well dimensioned, result in safe and high-quality products. Generally, pressure is transmitted instantly and evenly throughout the product (isostatic principle), regardless of the size and geometry of the food, unlike conventional thermal processing, where heat is gradually transferred through the food. Isostatic pressure can reduce time, energy consumption, and the risk of over-processing products.

In most situations, HPP is applied to previously packaged foods in order to optimize preservation processes and minimize product handling (López-Rubio et al., 2005). The most recommended materials for this application are based on flexible multilayer packaging of different combinations of polymers (Lambert et al., 2000; Marangoni Júnior, Cristianini, Padula, & Anjos, 2019; Richter, Sterr, Jost, & Langowski, 2010). However, as described in the scientific literature, high-pressure processing can lead to changes in the properties of packaging materials, which are influenced by time, temperature, pressure, and volume changes in addition to the effects of rapid compression and decompression (Ayvaz et al., 2012; Bull, Steele, Kelly, Olivier, & Chapman, 2010; Juliano, Koutchma, Sui, Barbosa-Cánovas, & Sadler, 2010; Marangoni Júnior et al., 2019).

In general, irreversible phenomena can occur in packaging materials exposed to high-pressure processing. According to Richter et al. (2010) the application of high-pressure can cause visible deformations, in addition to changes in material properties, that is, the functionality and visual appearance of the packaging material can be negatively affected. Therefore, evaluating the influence of different conditions of high-pressure processing on the properties of flexible packaging materials, such as morphological, thermal, mechanical, and barrier properties is essential for good performance during food processing, storage, distribution, and marketing.

In previous studies, our research group evaluated the effects of high-pressure processing on the morphological, thermal, and mechanical properties of different multilayer packaging materials, (Marangoni Júnior, de Oliveira, Bócoli, et al., 2020; Marangoni Júnior, de Oliveira, Dantas, et al., 2020). However, to complement these studies, it is necessary to evaluate the barrier properties after high-pressure processing. Regarding the barrier of packaging materials for products processed by high-pressure, there are two important aspects that must be considered: the performance of these materials in relation to changes in barrier characteristics and, the required properties of material to preserve the quality of packaged foods (Marangoni Júnior et al., 2019).

Therefore, in order to understand whether HPP can alter other functional properties of packaging materials, this research aimed to evaluate the influence of high-pressure processing on the barrier properties of flexible multilayer packaging, as well as to discuss whether these possible changes can affect the shelf life of food.

2 | MATERIAL AND METHODS

2.1 | Materials

Five flexible packages with differences in composition (Table 1) were used to produce 80 × 150 mm packages that were heat sealed by electrical impulse (Haramura - A380 Regente, São Paulo, Brazil).

The LDPE/PA/LDPE was obtained through the coextrusion process, the PA layer being responsible for the oxygen barrier that regulates the permeation of oxygen from the outside to the inside of the package and also for the mechanical resistance to minimize holes in places like corners and ends of the packages. The inner layer of LDPE

TABLE 1 Packaging materials evaluated in the study

Packaging material	Total thickness (μm)	Partial thickness (μm)
LDPE/PA/LDPE	100.2 ± 3.9	39.9 ± 1.8/18.0 ± 0.6/42.6 ± 2.4
LDPE/EVOH/LDPE	70.2 ± 1.7	29.8 ± 2.3/11.2 ± 0.8/29.4 ± 1.1
PET/LDPE/PA/EVOH/PA/LDPE	64.7 ± 1.1	13.4 ± 0.6/16.6 ± 0.4/4.8 ± 0.5/3.8 ± 0.3/5.1 ± 0.4/20.5 ± 0.6
PET/Al/PA/PP	155.4 ± 0.9	13.2 ± 1.0/13.2 ± 0.8/28.4 ± 1.1/100.2 ± 1.4
$PET_{printing}/PET_{met}/LDPE_{coex}$	100.5 ± 0.3	11.6 ± 1.9/15.5 ± 1.1/72.6 ± 1.2

Note: Thickness values refer to the average of five determinations in five samples ± standard deviation. The determination of the total thickness and of each layer of the samples were carried out through the analysis of images captured by an optical microscope (Leica - DM750, Buffalo Grove, USA) operating with a 200-fold magnification, using the Axio Vision image analysis system, from Zeiss company. For the preparation of the specimen, a microtome (Leica - RM2245, Buffalo Grove, USA) was used with a cut thickness positioned at 40 μm, as described in Sarantópoulos and Teixeira (2017).

is responsible for heat sealing. In addition, the inner and outer LDPE layer provides mechanical strength and protection for the PA layer against moisture. This material is used in packaging for meat and cheeses products submitted to vacuum before closing (Marangoni Júnior, de Oliveira, Bócoli, et al., 2020).

In the LDPE/EVOH/LDPE coextruded material, EVOH is responsible for the oxygen barrier and the internal LDPE layer for heat sealing. In general, this material is also used in vacuum meat and cheese products packaging (Marangoni Júnior, de Oliveira, Bócoli, et al., 2020).

In PET/LDPE/PA/EVOH/PA/LDPE coextruded material, PET is very transparent and is usually printed internally to protect the print, in addition to helping with the mechanical resistance of the packaging, LDPE as an adhesive, PA layers and EVOH for oxygen barrier and the inner layer of LDPE for heat sealing. This material is used as a film for thermoformed tray covers for sliced meat and cheeses products, but it can also be used in systems with modified atmosphere (Marangoni Júnior, de Oliveira, Bócoli, et al., 2020).

The PET/Al/PA/PP was produced by coextrusion and lamination and the combination of these materials results in the following properties: PET for abrasion resistance and excellent optical properties, Al provides a barrier to gases, vapors and aromas, PA mechanical and thermal resistance, and PP for heat sealing characteristics. This structure is intended for packaging sterilized products (foods with low acidity in general) and marketed at room temperature, such as ready-made meat and vegetable dishes, pet food sachets, among others, (Marangoni Júnior, de Oliveira, Dantas, et al., 2020).

The $PET_{printing}/PET_{met}/LDPE_{coex}$ was produced by coextrusion, metallization, printing, and lamination, so that PET provides abrasion resistance and excellent optical properties, besides that, when metallized, PET contributes to the barrier to gases and water vapor. LDPE makes it possible to heat seal the material. This structure is used for packaging sauces, pastes and purees, such as tomato sauce (Marangoni Júnior, de Oliveira, Dantas, et al., 2020).

2.2 | Packaging preparation

The packages of different materials were filled with 70 ml of food simulant: A (nonacidic aqueous food simulant (pH > 4.5)) distilled water, followed by heat sealing after applying a vacuum to minimize head space (Selovac - 200, São Paulo, Brazil).

2.3 | Processing

The packages were processed in two high-pressure conditions: 600 MPa/90°C/10 min (to assess the synergistic effect of high-pressure and high-temperature) and 600 MPa/25°C/10 min (to assess the high-pressure effect at room temperature). The average time of pressure increase was approximately 2 min and the average time of decompression was less than 30 s. The temperature of the equipment's chamber block and the initial water temperature were adjusted for the different processing conditions, taking into account the rate of temperature increase in the equipment's adiabatic conditions (3°C/100 MPa), the process temperature was reached after pressurization of 600 MPa. The experiments were carried out with a high-pressure pilot equipment (QFP 2L-700, Avure Technologies, OH, USA) that operates at pressures up to 690 MPa and temperatures up to 90°C. Water was used as a pressure-transmitting fluid. For comparison purposes, atmospheric pressure processing was carried out to evaluate the isolated effect of high-temperature. The packages were processed in an ultra-thermostatic bath (MA184, Marconi, Piracicaba, Brazil) at 0.1 MPa/90°C/10 min. Duplicates of the processes were carried out. Control (unprocessed) packaging was prepared for comparative purposes. After the different processing conditions, the packages were emptied and conditioned at 23 ± 2°C/75% RH for at least 48 hr. Then, the permeability tests were carried out. Figure 1 illustrates the experimental scheme.

2.4 | Assessment of barrier properties

2.4.1 | Water vapor transmission rate (WVTR)

The WVTRs were determined in equipment with an infrared sensor - PERMATRAN - (3/34 G, MOCON, Minneapolis, USA) according to the procedure described in ASTM F1249-13 (2013). The effective

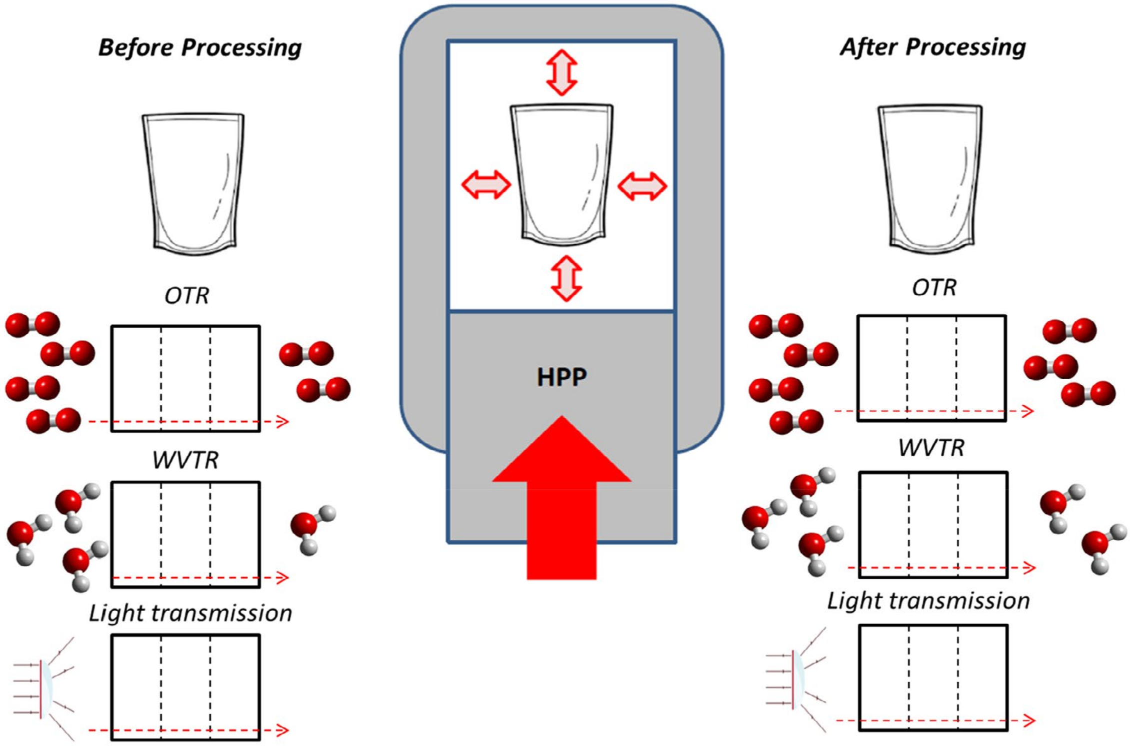

FIGURE 1 Experimental design of the study

permeation area of each specimen was 5 cm^2 and the test was conducted at 38 °C/90% RH in three repetitions.

2.4.2 | Oxygen transmission rate (OTR)

OTRs were determined according to the ASTM D1927-14 (2014) standard, in OXTRAN equipment (2/22 H, MOCON, Minneapolis, USA), operating with oxygen (99.99%) as permeant gas. The readings were corrected for 1 atm of partial pressure gradient of the permeant gas. The permeation area was 5 cm^2 and the tests were performed at 23°C and at 75% RH ± 0.1% RH, in three repetitions.

2.4.3 | Light transmission

The light transmission of the materials was performed in three repetitions and determined using a double-beam UV-visible spectrophotometer (Analytik Jena - Specord 210), with a scanning speed of 120 nm/min in a scanning range from 200 to 800 nm, according to procedure described in ASTM E1348-15 (2015).

2.5 | Statistical analysis

The results were reported as mean ± standard deviation and statistically evaluated by analysis of variance (ANOVA) and Tukey's test to compare the mean values ($p < 0.05$).

3 | RESULTS AND DISCUSSION

3.1 | WVTR and OTR

The WVTR results of the packaging materials, before and after the processing, shown in Table 2, demonstrate in the unprocessed packaging (control), that the materials that presented the greatest barrier to water vapor were PET/Al/PA/PP due to the presence of aluminum foil and PET$_{printing}$/PET$_{met}$/LDPE$_{coex}$ due to metallization on the PET film directly, without the presence of printing between the PET film and the metallization, which minimizes discontinuity in the aluminum deposition layer on the PET film. These materials are used to pack products with a longer shelf life in which moisture loss or gain must be avoided during storage.

Among the LDPE/PA/LDPE packages, there was no significant difference ($p <0.05$) in the WVTR after the different processing conditions (ranging from 3.93 ± 0.29 to 4.42 ± 0.10 g water.m^{-2}.day^{-1}). For LDPE/EVOH/LDPE, PET/LDPE/PA/EVOH/PA/LDPE, and PET/Al/PA/PP packaging, there was a significant increase ($p < 0.05$) in WVTR after processing at 600 MPa/90°C/10 min, when compared to control packaging. In addition, the results of this processing condition did not differ significantly from processing at 0.1 MPa/90°C/10 min, that is, the increase in WVTR of these materials was mainly influenced by the high-temperature of the processing. All processing conditions resulted in a significant increase ($p < 0.05$) in the WVTR of the PET$_{printing}$/PET$_{met}$/LDPE$_{coex}$ material compared to the control.

The OTR results presented in Table 2 show that among the unprocessed packages, those with the greatest oxygen barrier were

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TABLE 2 Water vapor transmission rates (WVTR) at 38°C/90% RH and oxygen transmission rates (OTR) at 23°C/75% ± 0.1% RH and 1 atm of partial oxygen pressure gradient

Packaging material	Processing condition	WVTR (g water.m^{-2}.day^{-1})	OTR (mL(STP).m^{-2}.day^{-1})
LDPE/PA/LDPE	Control	3.93 ± 0.29^{a}	86.30 ± 1.46^{b}
	600 MPa/25°C/10 min	4.13 ± 0.48^{a}	89.20 ± 4.21^{b}
	600 MPa/90°C/10 min	4.23 ± 0.21^{a}	99.00 ± 4.08^{a}
	0.1 MPa/90°C/10 min	4.42 ± 0.10^{a}	98.60 ± 3.30^{a}
LDPE/EVOH/LDPE	Control	4.88 ± 0.13^{b}	1.01 ± 0.32^{c}
	600 MPa/25°C/10 min	5.24 ± 0.25^{ab}	1.60 ± 0.20^{bc}
	600 MPa/90°C/10 min	5.92 ± 0.35^{a}	2.27 ± 0.23^{a}
	0.1 MPa/90°C/10 min	5.99 ± 0.40^{a}	2.20 ± 0.20^{ab}
PET/LDPE/PA/EVOH/PA/LDPE	Control	7.04 ± 0.13^{b}	4.17 ± 0.49^{c}
	600 MPa/25°C/10 min	6.99 ± 0.23^{b}	5.73 ± 0.31^{b}
	600 MPa/90°C/10 min	7.76 ± 0.08^{a}	6.87 ± 0.42^{a}
	0.1 MPa/90°C/10 min	7.51 ± 0.05^{a}	7.13 ± 0.42^{a}
PET/Al/PA/PP	Control	0.09 ± 0.07^{b}	<0.05[1]
	600 MPa/25°C/10 min	0.19 ± 0.07^{ab}	<0.05[1]
	600 MPa/90°C/10 min	0.31 ± 0.07^{a}	<0.05[1]
	0.1 MPa/90°C/10 min	0.28 ± 0.08^{ab}	<0.05[1]
$PET_{printing}/PET_{met}/LDPE_{coex}$	Control	2.29 ± 0.43^{b}	0.55 ± 0.08^{d}
	600 MPa/25°C/10 min	3.54 ± 0.14^{a}	2.60 ± 0.40^{c}
	600 MPa/90°C/10 min	3.81 ± 0.16^{a}	7.20 ± 0.87^{a}
	0.1 MPa/90°C/10 min	4.10 ± 0.12^{a}	4.87 ± 0.31^{b}

Note: Values referring to the mean of three determinations ± standard deviation. Means of the same material followed by the same letter do not differ at the 95% confidence level ($p < 0.05$).

[1]Results below the quantification limit of OXTRAN 2/22 equipment.

those of PET/Al/PA/PP, $PET_{printing}/PET_{met}/LDPE_{coex}$, and LDPE/EVOH/LDPE due to the presence of the foil aluminum and metallization on the PET film directly, without the presence of printing between the PET film and the metallization as discuss previously. And LDPE/EVOH/LDPE because the presence of EVOH film with thicker than 10 μm. Coextruded films with EVOH content are widely used in packaging for vacuum-packed meat and cheese.

After the different processing conditions, the PET/Al/PA/PP packaging material showed no significant difference ($p < 0.05$) in the OTR, compared to the control packaging material. However, the OTR of LDPE/PA/LDPE, LDPE/EVOH/LDPE, and PET/LDPE/PA/EVOH/PA/LDPE were higher after the different processes, the biggest significant difference ($p < 0.05$) after processing high-pressure combined with high-temperature (600 MPa/90°C/10 min) and atmospheric pressure processing at high-temperature (0.1 MPa/90°C/10 min), showing that high-temperature can result in loss of oxygen barrier of these materials. All processing and control conditions differed significantly ($p < 0.05$) from each other in the OTR of the $PET_{printing}/PET_{met}/LDPE_{coex}$ material, with the condition of 600 MPa/90°C/10 min resulting in a lower barrier to oxygen (before processing 0.55 ± 0.08 and after processing 7.20 ± 0.87 ml (STP “standard temperature and pressure”).m^{-2}.day^{-1}).

The increases in WVTR and OTR of PET/LDPE/PA/EVOH/PA/LDPE packaging after processing, partly due to changes in the thermal properties of PET, LDPE, and PA after processing at 90°C, in addition to defects on the material surface, as reported in our previous study (Marangoni Júnior, de Oliveira, Bócoli, et al., 2020). For the LDPE/EVOH/LDPE packaging, the loss of barrier to water vapor and oxygen may be the result of the plasticizing effect of water on EVOH, where probably the LDPE layer of this coextruded material was not sufficient to prevent EVOH contact with humidity during high-temperature (90°C), high-pressure (600 MPa), and high-humidity (water) from the processing, similar to what occurred in the study by Dhawan et al., 2014; Halin, Pascall, Lee, & Finnigan, 2009. In addition, López-Rubio et al. (2005) and Dhawan et al. (2014) raised a hypothesis in which the plasticization of EVOH could lead to a decrease in the interactions between the polymer chains, resulting in an increase in free volume and consequently negatively impacting the barrier properties of the material.

However, changes in WVTR are small and are likely to result in little or no moisture loss of food packaged and processed under high-pressure, as meat or cheese products which will also be influenced by the time, temperature, and relative humidity of the products' storage. In relation to OTR, it is recommended to evaluate case by case, taking into account that oxidation of fat and other food ingredients as vitamins, colors, and aroma compounds is one of the most important causes of quality losses during food processing and storage.

Lipid oxidation is a very complex reaction system, and when lipids in food are oxidized, a rancid flavor is formed. Basically, it is a free radical reaction which is influenced by a number of factors, one of them being oxygen availability. The oxygen amounts needed to cause unacceptable oxidative changes are usually very small. In fruit juice, the oxidation process is usually the ascorbic acid oxidation, but other pigments as anthocyanin or chlorophyll can oxidize (Damodaram, Parkin, & Fennema, 2010).

In this case, the user of the material will be able to determine if the changes in the OTR may or may not impact the quality of the packaged product. A critical factor for the oxidation reaction to occur is the availability of oxygen. In a packed food product, the oxygen content in the headspace, if there is a headspace, is usually much greater than the oxygen content in the product itself, due to the low solubility of oxygen in food compared to the possible oxygen concentration in the gas phase. The solubility of oxygen fat products is higher than in water products. And then, the oxygen dissolved in the product is also important, as it can influence the oxidation rate.

When packaging oxygen-sensitive foods, the time to the sensory limit for consumption was reached were dependent on the status of the product at the beginning of the storage, the temperature during storage, the oxygen permeability of the package and the oxygen availability in the packaging.

For the $PET_{printing}/PET_{met}/LDPE_{coex}$ laminate, the increases in WVTR and OTR are justified by the microscopic damage presented on the surface of the material, as reported in a previous study (Marangoni Júnior, de Oliveira, Dantas, et al., 2020). In addition, other studies in the literature, where metallized structures or other coatings, processed by different high-pressure conditions were also evaluated, resulting in discontinuation of metallization after high-pressure processing (Al-Ghamdi, Sablani, Rasco, & Cánovas, 2019; Ayvaz et al., 2012; Bull et al., 2010; Caner, Hernandez, & Pascal, 2000; Galotto, Ulloa, Guarda, Gavara, & Miltz, 2009; Galotto et al., 2010), which was not possible to evaluate the material studied due to the presence of printing on the outer layer of PET.

3.2 | Light transmission

Figure 2 shows the light transmission spectra of multilayer packaging before and after the different processes. The transmittance values of the PET/Al/PA/PP and $PET_{printing}/PET_{met}/LDPE_{coex}$ control materials are close to zero in the entire scanning range (200–800 nm), resulting from the light barrier that the aluminum foil, printing, and metallization add to the materials.

In the transparent materials LDPE/EVOH/LDPE and LDPE/PA/LDPE (control), it is observed that from the wavelength from 250 to 800 nm (which includes ultraviolet (<400 nm) and visible light (400–700 nm) (Jaime, Bócoli, Miguel, Ferreira, & Alves, 2018)), high light transmission occurs (90%). In the material PET/LDPE/PA/EVOH/PA/LDPE (control), up to a wavelength of 300 nm, this material had a high light barrier and from 300 to 800 nm, with 90% transmittance.

The light transmission properties depend on the thickness of the material and different plastic materials have different light transmission properties. Clear plastics do not provide a satisfactory light barrier and pigments can be incorporated into plastics for blocking light as amber, ruby, and brown. UV absorbers can be incorporated too, but normally they will absorb below 400 nm and are, therefore, not a complete solution to the light problem.

The transmittance of these same materials, after the different processing conditions, were not modified by the processing, although some materials showed superficial microscopic defects after processing, as demonstrated by Marangoni Júnior, de Oliveira, Bócoli, et al., (2020), Marangoni Júnior, de Oliveira, Dantas, et al. (2020), these defects did not interfere with the light transmission of the packaging.

Therefore, PET/Al/PA/PP and $PET_{printing}/PET_{met}/LDPE_{coex}$ material, the aluminum foil completely block light and metallized laminated film constructions also provide a good protection against light-induced changes. On the contrary, the use of transparent packaging has great marketing appeal, as it allows consumers to see the product they want to buy. However, the light that passes through the packaging material and can catalyze oxidation reactions in photo-sensitive products and shorten their useful life.

The major effects of light on foods are lipid oxidation and vitamin destruction. In meet, an additional effect is discoloration due to oxidation of the pigment myoglobin. Lipid oxidation due to light can take place by free radical autoxidation and/or photosensitized oxidation. Free radical autoxidation is catalyzed by light of short wavelengths in the visible spectrum and ultra-violet radiation. Photosensitized oxidation, on the contrary, takes place with light of all wavelengths. However, photosensitized oxidation requires a sensitizer that can absorb the energy. Common sensitizers in foods are chlorophyll, riboflavin, anthocyanin, and myoglobin.

The greatest effect of riboflavin, the water-soluble vitamin B_2 destruction occurs around 365 and 445 nm ranges, since it can act as a photosensitizer to be present in liver, egg, and dairy products. Yeast is also rich in riboflavin, and fermented beverages like beer contain significant concentration of riboflavin. Products as beer, milk, cheese, liver pâtés, and egg-based desserts have quality deterioration as resulting of riboflavin photosensitization and its affected storage stability and nutritive value and its important minimized through low access to oxygen and by avoiding visible light exposure, especially of wavelength 405 and 426 nm present with high-intensity in light from fluorescents tubes (Cardoso, Libardi, & Skibsted, 2012).

The factors affecting on shelf life and product quality of light-sensitive foods are: product characteristics (unsaturated fat, protein, prooxidants as Cu and Fe, antioxidants as carotenoids, tocopherols and ascorbic acid, pH, water activity, etc.), processing in open-vat productions, light transmission packaging material, oxygen level in head space, light source intensity, exposure time, temperature,

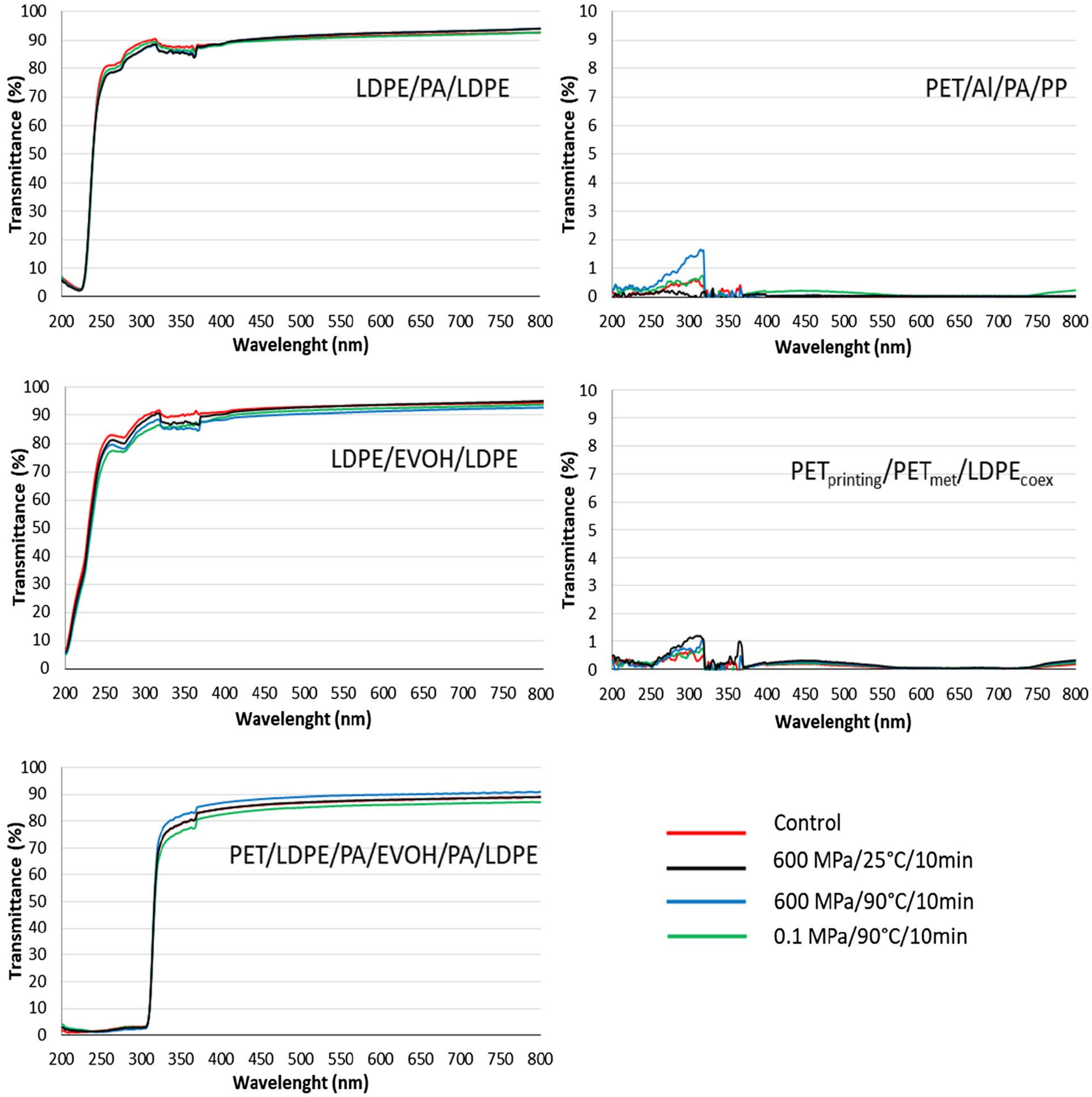

FIGURE 2 Spectrum of light transmittance (%) of different packaging materials processed by high-pressure. Average results from three repetitions

and relative humidity (Mortensen, Bertelsen, Mortensen, & Stapelfeldt, 2004).

4 | CONCLUSIONS

High-pressure processing at different temperatures did not affect the light barrier properties of the different packaging materials tested. Regarding the water vapor and oxygen barrier properties, the combination of high-pressure and high-temperature (600 MPa/90°C/10 min) significantly increased the WVTR of packaging of LDPE/EVOH/LDPE, PET/LDPE/PA/EVOH/PA/LDPE, and $PET_{printing}/PET_{met}/LDPE_{coex}$, and the OTR of packaging of LDPE/PA/LDPE, LDPE/EVOH/LDPE, PET/LDPE/PA/EVOH/PA/LDPE, and $PET_{printing}/PET_{met}/LDPE_{coex}$, which can impact the stability of packaged foods.

In general, the high-temperature (90°C) of the processing had a greater influence on the water vapor and oxygen barrier properties of the films than the high-pressure (600 MPa), however, the synergistic effect of high-temperature and high-pressure resulted in greater loss of barrier of the evaluated films. However, it is noteworthy that it is important to know the composition of the food to be packaged and processed by high-pressure, in addition to the time and temperature and relative humidity conditions in which these products will be stored/marketed, to diagnose whether the changes reported in the properties of material barrier after high-pressure processing will impact the nutritional and sensory characteristics of the food and the loss of shelf life.

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

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