Food Packaging and Shelf Life 26 (2020) 100576

Contents lists available at ScienceDirect

Food Packaging and Shelf Life

journal homepage: www.elsevier.com/locate/fpsl

Effect of high-pressure processing on the migration of ε-caprolactam from multilayer polyamide packaging in contact with food simulants

Luís Marangoni Júnior [a,b,*], Mary Ângela Fávaro Perez [b], Caroline Donadon Torres [b], Marcelo Cristianini [a], Paulo Henrique Massaharu Kiyataka [b], Aline Cristina Albino [b], Marisa Padula [b], Carlos Alberto Rodrigues Anjos [a]

[a] Department of Food Technology, School of Food Engineering, University of Campinas, Campinas, São Paulo, Brazil
[b] Packaging Technology Center, Cetea, Institute of Food Technology, Ital, Campinas, São Paulo, Brazil

ARTICLE INFO

Keywords:
Flexible packaging
Food contact material
Food safety
Emerging technologies
Specific migration
Overall migration

ABSTRACT

Polyamide is a material widely used as food packaging. However, residual monomers can migrate from polyamide food packaging into food during the processing and storage conditions. Hence, it is necessary to evaluate the effect of processing carried out with emerging technologies, taking this issue into consideration. This research presents for the first time the effect of high-pressure processing on the ε-caprolactam migration from multilayer polyamide packaging to different food simulants. Commercial LDPE/PA/LDPE and PET/LDPE/PA/EVOH/PA/LDPE packaging materials were filled with 70 mL of food simulant (acid, aqueous, and fatty) and processed at 600 MPa/25 °C/10 min, 600 MPa/90 °C/10 min, and 0.1 MPa/90 °C/10 min. Samples were evaluated as for ε-caprolactam overall and specific migration after processing and after conditioning at 40 °C/10 days. The migration of ε-caprolactam to the distinct simulants after different processing was greater when processed under atmospheric pressure and high-temperature (0.1 MPa/90 °C/10 min) than when processed under high-pressure (600 MPa). All evaluated samples showed specific migration values of ε-caprolactam lower than 15 mg kg^{-1}. Therefore, under the assessed conditions, the materials comply with the limits of the ε-caprolactam specific migration for the current legislation.

1. Introduction

Plastic materials are widely employed in food packaging applications for their excellent properties, especially when combined with multilayer packaging through co-extrusion and/or lamination processes. Some of the most used polymers in this application include polyethylene (PE), polyethylene terephthalate (PET), polypropylene (PP), polystyrene (PS), ethylene vinyl alcohol (EVOH), polyvinyl chloride (PVC), and polyamide (PA) (Ibarra, De Quirós, Losada, & Sendón, 2019; Robertson, 2013). The packaging must provide physical protection and prolong the shelf life of the food; however, when the packaging comes into contact with the food, some of its components may migrate to the food (Mccombie, Biedermann, & Authority, 2019).

Food contact materials (FCMs) are intended for the protection and preservation of food. However, their contact with food can cause the migration of distinct substances, becoming vehicles for their contamination (Blanco-Zubiaguirre et al., 2020). Substances that migrate from the packaging to the products can affect the sensory quality and the toxicity level of the packaged products (Marangoni Júnior, Cristianini, Padula, & Anjos, 2019; Marangoni Júnior, Cristianini, & Anjos, 2020). These substances include low molecular weight substances, organic solvents, plasticizers, antioxidants, and monomers, among others. Overall, the migration of packaging material to food simulants depends on the initial concentration of the migrant, the diffusion coefficient of the migrant in the packaging material, and the interaction between the packaging and the food simulant (Stoffers et al., 2005). In other words, migration increases with the amount of migrant in the material, the solubility of the migrant in the simulant, and the contact conditions.

Abbreviations: EVOH, ethylene vinyl alcohol; FCMs, food contact materials; GC, gas chromatography; HPP, high-pressure processing; LDPE, low-density polyethylene; MDPE, medium-density polyethylene; PA, polyamide; PE, polyethylene; PET, polyethylene terephthalate; PP, polypropylene; PS, polystyrene; PVC, polyvinyl chloride; Zn, zinc.

* Corresponding author at: Rua Monteiro Lobato, 80 – Cidade Universitária Zeferino Vaz, CEP: 13083-862, Campinas, São Paulo, Brazil.
E-mail address: marangoni.junior@hotmail.com (L. Marangoni).

https://doi.org/10.1016/j.fpsl.2020.100576
Received 8 May 2020; Received in revised form 18 September 2020; Accepted 25 September 2020
Available online 21 October 2020

Substances with low molecular weight are more likely to migrate than those with higher molecular weight, as described by Heimrich, Nickl, Bönsch, and Simat (2015).

Polyamides, commercially known as Nylons®, are widely used in flexible multilayer packaging because they demonstrate good mechanical performance, heat resistance, and oxygen barrier, in addition to being linear polymers, with a sequence of amide groups in the chain and being produced by polymerization of the ε-caprolactam in the material PA6 (Lai et al., 2019; Robertson, 2013). Polymerization reactions result from low molecular weight compounds, and such reactions generally result in high molecular weight substances, but the monomer conversion is less than 100 % (Bomfim, Zamith, & Abrantes, 2011; Song, Chang, & Lyu, 2018). Therefore, the residual monomer, that is, when not completely polymerized, remains in the resin and can migrate from packaging to food (Araújo, Felix, Manzoli, Padula, & Monteiro, 2008; Song et al., 2018). In addition, oligomers and degradation compounds may also be present and migrate to food (simulants) (Félix, Padula, Manzoli, & Monteiro, 2006).

Specific migration limits are regulated by government agencies such as Board Resolution – RDC No. 56/2012 and RDC No. 326/19, from the National Health Surveillance Agency Brazil (ANVISA) (Brazil, 2012, 2019), and Regulation No. 10/2011, from the European Union (European-Commission, 2011). These regulations have a maximum migration limit of ε-caprolactam of 15 mg kg^{-1} of food simulant.

Futhermore, many foods are processed inside the packaging such as pasteurization, sterilization, microwaves, high-pressure processing, among others. High-pressure processing (HPP) is an emerging technology in food processing, aiming to increase the stability of products, considering that it acts as a cold pasteurization process, thus minimally affecting sensory and nutritional attributes (Hernández-Hernández, Moreno-Vilet, & Villanueva-Rodríguez, 2019). When aiming at food sterilization, high-pressure processing is combined with high-temperature, resulting in better quality products when compared with commercial sterilization (Koutchma et al., 2010; Marangoni Júnior, Alves et al., 2020; Marangoni Júnior, Oliveira, Dantas et al., 2020).

Therefore, the selection of packaging material becomes essential. Flexible packaging structures, which return to their initial position, are the most recommended in high-pressure processing, taking into account that the compression caused by high-pressure decreases the volume of the plastic material and, therefore, there may be changes in the ability to interact with food. When the pressure is released, the packaging material must recover its original characteristics, according to which the interactions must be similar to those expected at atmospheric pressure (Prakasam & Largeteau, 2017).

In the scientific literature, there are few studies on the influence of high-pressure processing on the migration potential of packaging materials, as reported in the review conducted by Marangoni et al. (2019), requiring further evaluations of the effect of this technology on the migration of different components of the most diverse packaging materials available on the market. In addition, it is necessary to evaluate the various conditions of high-pressure processing to obtain a diagnosis of the potential for packaging migration. Moreover, according to Caner and Harte (2005), food manufacturers using HPP technology must ensure the quality and safety of their food products, and it is necessary to understand the issues of mass transfer between packaging material and food simulants to ensure consumer confidence.

The aim of this study was to evaluate the effect of high-pressure processing, at room temperature and at high temperature, compared with conventional heat treatment on the overall and specific migration of ε-caprolactam from multilayer food packages containing polyamide. Packaging materials in contact with different food simulants were considered. To the best of our knowledge, this the first time that the migration of this monomer is investigated considering the aforementioned emerging technology.

2. Material and methods

2.1. Standards and reagents

The standards used for the analysis were: ε-caprolactam (99.5 % purity, Chem Service, USA) and 2-aza-cyclo-nonanone (99.8 % purity, TCI, Japan). The reagents used for the tests were: olive oil (Andorinha, Portugal), glacial acetic acid (Merck, Germany), methanol (≥99.9 %, Merck, Germany), n-heptane PA (99 %, Synth, Brazil), and ethyl alcohol (≥99.9 %, Merck, Germany).

2.2. Packaging materials

Two multilayer packaging materials containing polyamide were used in this study (Table 1). Packages with dimensions of 80 mm x 150 mm were filled with 70 mL of different food simulants (240 cm^2 or 2.4 dm^2 of packaging contact surface with food simulants) and heat sealed (Haramura – A380 Regente, São Paulo, Brazil).

The materials used for the overall migration tests were filled with two food simulants: simulant A (nonacidic aqueous food simulant (pH > 4.5): distilled water; simulant B (acidic aqueous food simulant (pH ≤ 4.5): 3 % (w/v) acetic acid solution in distilled water, followed by processing. For the analysis of the specific migration potential of ε-caprolactam, in addition to simulants A and B, simulant D (fatty food simulant): olive oil was used, as described by RDC No. 51, of November 26, 2010 from ANVISA (Brazil, 2010).

2.3. High-pressure processing

Samples filled with the different food simulants were processed in a high-pressure pilot equipment (QFP 2L-700, Avure Technologies, OH, USA) that operates with pressures up to 690 MPa and temperatures up to 90 °C. Two high-pressure processing conditions were used: 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 pressure increase time was approximately 2 min, and the decompression time was less than 30 s. The temperature of the chamber block of the equipment and the initial water temperature were adjusted for the different processing conditions, considering the rate of temperature increase in the adiabatic conditions of the equipment (3 °C/100 MPa), and the process temperature was reached after pressurization at 600 MPa. Water was used as a pressure-transmitting fluid. In addition, processing at atmospheric pressure was obtained to evaluate the isolated effect of temperature, and the packages were processed in an ultra-thermostatic bath (MA184, Marconi, Piracicaba, Brazil) at 0.1 MPa/90 °C/10 min. Control samples (unprocessed) were prepared for comparative purposes.

Table 1
Specification of packaging materials.

Packaging Material	Partial thickness (μm)	Total thickness (μm)	Examples of applications
LDPE/PA/LDPE	40/18/42	100	This material is used as packaging for vacuum-packed meat products and cheeses (Marangoni Júnior, Oliveira, Bócoli et al., 2020).
PET/LDPE/PA/EVOH/PA/LDPE	13/16/5/4/5/22	65	This material is used as a film to cover thermoformed trays for sliced meat products and cheeses and in packaging systems with modified atmosphere (Marangoni Júnior, Oliveira, Bócoli et al., 2020).

LDPE: low-density polyethylene; PA: polyamide; PET: polyethylene terephthalate; EVOH: ethylene and vinyl alcohol copolymer.

2.4. Overall migration

Packages were evaluated as for overall migration before being processed and after the different processing conditions. Furthermore, considering that the food would be subjected to high-pressure processing in the same packaging that will be marketed, more predictable and critical contact conditions were employed, with contact time exceeding 24 h and contact temperature of 20–40 °C, that is, test time of 10 days at 40 °C in an oven (BD400, Binder).

Overall migration tests were carried out according to the standards EN 1186-9 (2002) and EN (1186)-1 (2002) in compliance with RDC No. 51/10 (Brazil, 2010). After processing and conditioning periods, the overall migration was determined according to the gravimetric method. The food simulants were evaporated in the heating plate (TE-038, Tecnal). An analytical balance with 0.00001 g accuracy was used (MSA225P-1CE-DA, Sartorius). The test was conducted with four repetitions.

2.5. Specific migration

After the different processes, samples were evaluated for specific migration of ε-caprolactam. In addition, the control sample and processed samples were conditioned in an oven (400-5ND, Ethik Technology, Vargem Grande Paulista, Brazil) at 40 °C/10 days, simulating the most critical condition of food storage determined by the RDC Legislation No. 51/2010 from ANVISA (Brazil, 2010) and the EU Regulation No. 10/2011 (European-Commission, 2011).

2.5.1. Preparation of simulants

A standard stock solution was made of 0.05185 g or 51.85 mg ε-caprolactam in 100 mL of methanol (0.5185 mg mL^{-1} or 518.5 μg mL^{-1}), and the internal standard stock solution was made of 0.03584 g or 35.84 mg 2-aza-cyclo-nonanone in 100 mL of methanol (0.3584 mg mL^{-1} or 358.4 μg mL^{-1}). Different volumes of the standard stock solution of ε-caprolactam were added to a series of 25 mL volumetric flasks, 0 mL, 1 mL, 2 mL, 4 mL, 6 mL, and 8 mL of the standard stock solution of ε-caprolactam. For each of the flasks 5 mL of the intenal stock solution of 2-aza-cyclo-nonanone and he volume was completed with methanol. The intermediate standard solution obtained were concentrations 0; 20.7; 41.5; 83.0; 124.4 and 165.9 μg mL^{-1} of ε-caprolactam and 71.7 μg mL^{-1} 2-aza-cyclo-nonanone in methanol.

After contact with the sample, 4.0 mL of the aqueous simulants (water and 3 % w/v acetic acid solution) were placed in test tubes with the aid of a micropipette. Then, 1.0 mL of 71.7 μg mL^{-1} 2-aza-cyclo-nonanone intermediate solution was added and mixed. A small amount of this solution was transferred to a 2.0 mL glass vial for injection in the gas chromatograph (GC).

The process was repeated for each of the analyzed specimens and for the simulant blank. The final concentration of the internal standard in the samples was 14.3 mg kg^{-1} of 2-aza-cyclo-nonanone.

To prepare the analytical curve, 4.0 mL of the aqueous simulants (water and 3 % w/v acetic acid solution) were used in a test tube, and 1.0 mL of an intermediate standard solution of 71.7 μg mL^{-1} of 2-aza-cyclo-nonanone, containing the following individual concentrations: 0; 20.7; 41.5; 83.0; 124.4; and 165.9 μg mL^{-1} of ε-caprolactam. The final concentrations obtained for the analytical curve in the aqueous simulants were approximately 0; 4.15; 8.30; 16.59; 24.89; and 33.18 mg kg^{-1} of ε-caprolactam with 14.3 mg kg^{-1} of internal standard (2-aza-cyclo-nonanone).

After contact with the sample, the fatty simulant was prepared as follows: 15 ± 1 g of olive oil was weighed on an analytical scale (MSA225P-1CE-DA, Sartorius AG, Goettingen, Germany). Then, 2.0 mL of intermediate standard solution of 71.7 μg mL^{-1} of 2-aza-cyclo-nonanone was added and mixed, 15.0 ± 1 mL of n-heptane was added to perform the extraction of olive oil, and 8.0 mL of a 1:2 (v/v) ethanol/water solution was also added. It was stirred for 10 min on an orbital shaking table (109-2, Ethik Technology, Vargem Grande Paulista/SP, Brazil), followed by resting for 30 min to separate the phases. Then, with the aid of a Fine Tip Pasteur pipette, approximately 2.0 mL of the aqueous phase of the solution was removed. Subsequently, the collected solution was filtered in a Pasteur pipette containing cotton at the tip to retain any residual oil in a 2.0 mL vial for injection into the GC. The process was repeated for each of the analyzed specimens and for the simulant blank. The final concentration of the internal standard after extraction was 9.3 mg kg^{-1} of 2-aza-cyclo-nonanone.

For the preparation of the analytical curve after weighing the 15.0 ± 1 g of olive oil, 2.0 mL of an intermediate standard solution of 71.7 μg ml^{-1} of 2-aza-cyclononanone was added, containing the following individual concentrations ion each erlemeyer: 0; 20.7; 41.5; 83.0; 124.4; and 165.9 μg mL^{-1} of ε-caprolactam. After extraction, as performed with the sample, the final concentrations obtained for the analytical curve in the fatty simulant were approximately 0; 2.77; 5.53; 11.06; 16.59; and 22.12 μg of ε-caprolactam per g^{-1} of olive oil with 9.56 μg of internal standard solution (2-aza-cyclo-nonanone) per g^{-1} of olive oil. It was considered 1 μg is equal to 1×10^{-3} mg and 1 g is equal 1×10^{-3} kg, than μg g^{-1} is the sameequals mg kg^{-1}. Hence, the concentration was 0; 2.77; 5.53; 11.06; 16.59; and 22.12 mg of caprolactam kg^{-1} and 9.56 mg of 2-aza-cyclo-nonanone kg^{-1}.

Water, 3 % w/v acetic acid solution, and olive oil were used as simulants assuming a density of 1. Thus, milligrams of substance released per liters of simulant will numerically correspond to milligrams of substance per kilograms of simulant.

2.5.2. Migration of ε-caprolactam by gas chromatography (GC)

The determination of the specific migration of ε-caprolactam was carried out according to the CEN/TS (1313)0-16 (2005) method of the European Standardization Committee, using the aqueous, acid, and fatty simulants. Tests were performed in a gas chromatograph with flame ionization detection (HP 6890 N, Agilent Technologies, China) and a liquid injector (G4513A, Agilent Technologies, China), operating with a capillary column (DB-17, Agilent J&W Capillary GC Columns, USA) (30 m × 0.53 mm × 1.5 μm). The initial column temperature was set at 180 °C min^{-1}, with a ratio of 10 °C min^{-1} to 200 °C, remaining at 200 °C for another 9 min (fatty simulant) and 7 min (aqueous and acid simulants). The running time was 12 min for the fatty simulant and 10 min for the aqueous simulants. Each specimen of the sample and the analytical curve was injected in duplicate. Injector and detector temperatures were 240 °C and 270 °C, respectively. The gas (helium) was maintained at a pressure of 3.98 psi with a constant column flow rate of 3.0 mL min^{-1}. Flow rates of hydrogen and oxygen were 40.0 and 80.0 mL min^{-1}, respectively. The volume of 1.0 μL was injected in the gas chromatograph with split in the 14:1 proportion. For the quantification of ε-caprolactam, an analytical curve with internal standardization of 2-aza-cyclo-nonanone was used. The test was carried out in four repetitions. The analytical figure of the merit of the method developed for each food simulant is presented in the Supplementary Material section.

2.6. Statistical analysis

The results were expressed as an average of four determinations and standard deviation, and were statistically evaluated by analysis of variance (ANOVA) and Tukey's test in order to compare the mean values.

3. Results and discussion

3.1. Overall migration

In Tables 2 and 3 the results of the overall migration of the LDPE/PA/LDPE and PET/LDPE/PA/EVOH/PA/LDPE films in contact with aqueous and acidic simulants evaluated after processing, and after

Table 2
Results of overall migration, in mg dm^{-2}[1], evaluated after the different processing conditions.

Packaging Material	Processing condition (10 min)	Food Simulants	
		Aqueous (distilled water)	Acid (3 % w/v acetic acid)
LDPE/PA/LDPE	600 MPa/25 °C	≤2.33[2]	≤2.33[2]
	600 MPa/90 °C	≤2.33[2]	≤2.33[2]
	0.1 MPa/90 °C	≤2.33[2]	≤2.33[2]
PET/LDPE/PA/EVOH/PA/LDPE	600 MPa/25 °C	≤2.33[2]	≤2.33[2]
	600 MPa/90 °C	≤2.33[2]	≤2.33[2]
	0.1 MPa/90 °C	≤2.33[2]	≤2.33[2]

The results are expressed as mean of four repetitions.
The overall migration test is accredited by ABNT NBR ISO/IEC 17025:2017and the limit of quantification is standard for all tests regardless of the packaging area used. The LOQ was calculated as the resolution of the balance (0.00001 g) multiplied by a factor of 100 and divided by an area of 0.43 dm^2.
[1] Applicable limit: 8.0 mg dm^{-2} and 10 mg dm^{-2} of simulant (10 % analytical tolerance), according to ANVISA Resolution No. 105/99 (Brazil, 1999) and EU Regulation No. 10/2011 (European-Commission, 2011), respectively.
[2] Limit of quantification of the method under the analytical conditions used.

Table 3
Results of overall migration, in mg dm^{-2}[1], evaluated before and after the different processing conditions and conditioned at 40 °C/10 days.

Packaging Material	Processing condition (10 min)	Food Simulants	
		Aqueous (distilled water)	Acid (3 % w/v acetic acid)
LDPE/PA/LDPE	Control	≤2.33[2]	≤2.33[2]
	600 MPa/25 °C	≤2.33[2]	≤2.33[2]
	600 MPa/90 °C	≤2.33[2]	≤2.33[2]
	0.1 MPa/90 °C	≤2.33[2]	≤2.33[2]
PET/LDPE/PA/EVOH/PA/LDPE	Control	≤2.33[2]	≤2.33[2]
	600 MPa/25 °C	≤2.33[2]	≤2.33[2]
	600 MPa/90 °C	≤2.33[2]	≤2.33[2]
	0.1 MPa/90 °C	≤2.33[2]	≤2.33[2]

The results are expressed as mean of four repetitions.
The overall migration test is accredited by ABNT NBR ISO/IEC 17025:2017ABNT NBR ISO/IEC 17025:2017 and the limit of quantification is standard for all tests regardless of the packaging area used. The LOQ was calculated as the resolution of the balance (0.00001 g) multiplied by a factor of 100 and divided by an area of 0.43 dm^2.
[1] Applicable limit: 8.0 mg dm^{-2} and 10 mg dm^{-2} of simulant (10 % analytical tolerance), according to ANVISA Resolution No. 105/99 (Brazil, 1999) and EU Regulation No. 10/2011 (European-Commission, 2011), respectively.
[2] Limit of quantification of the method under the analytical conditions used.

processing and conditioned at 40 °C/10 days are presented.

All evaluated samples showed results below the quantification limit of the employed method (≤2.33 mg dm^{-2}). All samples comply with the ANVISA Resolution No. 105/19 (Brazil, 1999) and the EU Regulation No. 10/2011 (European-Commission, 2011), since they presented overall migration values below the established limit of 8.0 mg dm^{-2} and 10 mg dm^{-2}, respectively. Therefore, in terms of overall migration, it can be said the evaluated packaging materials can be approved for contact with acidic and aqueous foods processed by high-pressure under the assessed conditions.

Our results of overall migration were similar to those found by Lambert et al. (2000). The authors found overall migration results <10 mg dm^{-2} for multilayer PA/MDPE, PA/LDPE (linear free radical), PA/Surlyn® (Zn ionomer), and PA-PP/LDPE (linear free radical) packaging in contact with different food simulants (distilled water, 15 % ethanol, and 3 % acetic acid and isoctane), which were processed at 200, 350, and 500 MPa, at 20 °C/30 min, and maintained at 40 °C/10 days.

3.2. Specific migration of ε-caprolactam

In Table 4 shows the results of the specific migration of ε-caprolactam from the LDPE/PA/LDPE flexible packaging in contact with different food simulants that were evaluated right after the different processing conditions. After processing 600 MPa/25 °C/10 min, the migration results of ε-caprolactam in aqueous, acid and fatty food simulants were below the quantification limit of the employed method, that is, ≤0.35, ≤0.84 and ≤0.30 mg kg^{-1}, respectively. For materials processed at 600 MPa/90 °C/10 min, the migration values of ε-caprolactam were below the quantification limit for aqueous and acid food simulants. However, for the fatty food simulant, this material showed a 0.46 mg kg^{-1} ε-caprolactam migration. In addition, when 0.1 MPa/90 °C/10 min processing was applied; the migration values of ε-caprolactam were 0.75, 1.03 and 1.00 mg kg^{-1} for aqueous, acidic and fatty food simulants, respectively.

A similar behavior was observed for the flexible packaging with PET/LDPE/PA/EVOH/PA/LDPE structure processed at 600 MPa/25 °C/10 min and 600 MPa/90 °C/10 min (Table 4). Regarding the results of materials processed at 0.1 MPa/90 °C/10 min, the migration of ε-caprolactam was 0.39 and 0.46 mg kg^{-1} for the simulants of aqueous and fatty foods, respectively. However, for the acid food simulant the values were below the limit of quantification.

Accordingly, when high pressures (600 MPa) are applied to the packaging material with different food simulants, the ε-caprolactam migration phenomenon is inferior when compared with conventional thermal processing (0.1 MPa/90 °C/10 min). According to Guillard, Mauricio-Iglesias, and Gontard (2010), Song (2014) and Ayvaz, Balasubramaniam, and Koutchma (2016), during high pressure compression, the polymer matrix loses its ability to interact with food due to the reduction of free volume. As the pressure is released, the polymer gradually recovers its original state and, therefore, migration processes can occur as expected at normal atmospheric pressure, which may explain the results of our study.

Although this phenomenon can be explained, must bear in mind that the number of reported experiments is too low to draw completely accurate conclusions. Hence, it is necessary and desirable to study more structures with polyamide processed under other conditions, such as: conventional sterilization (most frequent temperature of 121 °C) and pressure assisted thermal sterilization (pressures at >600 MPa and temperature at >100 °C) conditions, in which the high pressure pilot equipment used in this study could not be applied. Moreover, it is worth noting that the high process temperature (90 °C) had a significant effect on the migration of ε-caprolactam. According to Félix, Manzoli, Padula, and Monteiro (2014), high temperature favors the diffusion and solubility of low molecular weight compounds.

In addition to evaluating the migration of ε-caprolactam right after processing, the samples were conditioned at 40 °C/10 days, simulating the most critical foreseeable conditions of use. The migration of ε-caprolactam from the LDPE/PA/LDPE film to the aqueous and acid food simulants after processing 600 MPa/25 °C/10 min, 600 MPa/90 °C/10 min and, 0.1 MPa/90 °C/10 min and conditioning at 40 °C/10 days was significantly less ($p < 0.05$) than the control (Table 5). For the fatty food simulants, the migration of ε-caprolactam after the processing condition of 600 MPa/25 °C/10 min and conditioning at 40 °C/10 days did not significantly differ ($p < 0.05$) from the control. However, migration after the condition of 600 MPa/90 °C/10 min and processed at 600 MPa/25 °C/10 min was significantly less ($p < 0.05$) than the control. Furthemore, for the fatty simulant, the migration of ε-caprolactam after processing 0.1 MPa/90 °C/10 min and conditioning at 40 °C/10 days showed a significant increase ($p < 0.05$) when compared with the other conditions, which was influenced by the interaction of the fatty food simulant with the packaging material during the high temperature of the processing under atmospheric pressure.

For the PET/LDPE/PA/EVOH/PA/LDPE structure, the migration of ε-caprolactam in aqueous food simulants after the different processing

Table 4
Migration of ε-caprolactam in food simulants after different processing conditions.

Packaging Material	Processing condition (10 min)	Food Simulants		
		Aqueous (distilled water)	Acid (3 % w/v acetic acid)	Fatty (olive oil)
LDPE/PA/LDPE	600 MPa/25 °C	≤0.35[1]	≤0.84[1]	≤0.30[1]
	600 MPa/90 °C	≤0.35[1]	≤0.84[1]	0.46 ± 0.20[b]
	0.1 MPa/90 °C	0.75 ± 0.07	1.03 ± 0.06	1,00 ± 0,08[a]
PET/LDPE/PA/EVOH/PA/LDPE	600 MPa/25 °C	≤0.35[1]	≤0.84[1]	≤0.30[1]
	600 MPa/90 °C	≤0.35[1]	≤0.84[1]	≤0.30[1]
	0.1 MPa/90 °C	0.39 ± 0.02	≤0.84[1]	0.46 ± 0.02

The results are expressed as mean of four repetitions ± standard deviation.
[a,b,c]Averages followed by the same lowercase letters in the column do not differ at the 95 % confidence level ($p < 0.05$).
[1] Limit of quantification of the method under the analytical conditions used for the food simulants aqueous (≤0.35), acid (≤0.84) and fatty (≤0.30), respectively.

Table 5
Migration of ε-caprolactam in food simulants after different processing conditions and conditioned at 40 °C/10 days.

Packaging Material	Processing condition (10 min)	Food Simulants		
		Aqueous (distilled water)	Acid (3 % w/v acetic acid)	Fatty (olive oil)
LDPE/PA/LDPE	Control	1.78 ± 0.23[a]	2.58 ± 0.12[a]	1.89 ± 0.16[b]
	600 MPa/25 °C	1.54 ± 0.10[b]	1.76 ± 0.07[b]	1.66 ± 0.18[b]
	600 MPa/90 °C	1.29 ± 0.15[c]	1.80 ± 0.10[b]	1.24 ± 0.30[c]
	0.1 MPa/90 °C	1.20 ± 0.10[c]	1.33 ± 0.09[c]	2.41 ± 0.15[a]
PET/LDPE/PA/EVOH/PA/LDPE	Control	0.53 ± 0.05[a]	≤0.84[1]	0.41 ± 0.03[b]
	600 MPa/25 °C	0.59 ± 0.08[a]	≤0.84[1]	0.42 ± 0.04[b]
	600 MPa/90 °C	0.53 ± 0.06[a]	≤0.84[1]	0.31 ± 0.04[c]
	0.1 MPa/90 °C	0.61 ± 0.04[a]	≤0.84[1]	0.99 ± 0.03[a]

The results are expressed as mean of four repetitions ± standard deviation.
[a,b,c]Averages followed by the same lowercase letters in the column do not differ at the 95 % confidence level ($p < 0.05$).
[1] Limit of quantification of the method under the analytical conditions used for the acid food simulants (≤0.84).

conditions and conditioning at 40 °C/10 days did not significantly differ ($p < 0.05$) from the control and for the acid food simulants the results were below the method quantification limit (Table 5). Concerning the fatty food simulant, the migration of ε-caprolactam showed a behavior similar to the flexible packaging of LDPE/PA/LDPE, in which the migration after the processing condition of 600 MPa/25 °C/10 min and conditioning at 40 °C/10 days did not significantly differ ($p < 0.05$) from the control; the condition of 600 MPa/90 °C/10 min and conditioning at 40 °C/10 days resulted in significantly less migration ($p < 0.05$) than the control; and processing of 0.1 MPa/90 °C/10 min and conditioning at 40 °C/10 days showed a significant increase ($p < 0.05$) in the migration of ε-caprolactam when compared with the other conditions.

The results of this study are in agreement with the research by Padula et al. (2016) which evaluated a flexible packaging based on high barrier polyamide subjected to high-pressure processing at 600 MPa/7 °C/2 min using fatty food simulants (olive oil). The samples were evaluated before processing (conditioned at 40 °C/10 days), after processing and conditioned at 40 °C/10 days, and after processing and conditioned at 4 °C/120 days. The results migration of ε-caprolactam were 1.6, 1.9, and 1.5 mg kg^{-1} of simulant, respectively, that is, the processing had little influence on the results of specific migration of ε-caprolactam.

Furthermore, when comparing the results of the two packaging materials, observed that the LDPE/PA/LDPE packaging showed ε-caprolactam migration values higher than the results of the PET/LDPE/PA/EVOH/PA/LDPE. These findings were probably and mainly influenced by the thickness of the PA layer of the LDPE/PA/LDPE film, which is greater than the thickness of the PA layer of the PET/LDPE/PA/EVOH/PA/LDPE film, and which may consequently have a greater amount of ε-caprolactam residual monomers.

The sample of LDPE/PA/LDPE control conditioned at 40 °C/10 days in contact with acid simulant showed the highest migration value of ε-caprolactam (2.58 mg kg^{-1} of simulant). The acid food simulant is reported in the literature as the worst scenario for ε-caprolactam migration using polyamide materials due to its chemical nature and type of polymer (Bustos, Sendon, Sanchez, Paseiro, & Cirugeda, 2009; Félix et al., 2014). The migration of ε-caprolactam to aqueous simulants (distilled water and 3 % acetic acid solution) can be explained by the high affinity of water to PA due to the polarity of the amide group in the polymer, that is, the low solubility of the polar substance, such as ε-caprolactam, in a hydrophobic medium (Heimrich et al., 2015). In addition, as described by Heimrich et al. (2015), and Stoffers et al. (2005), it is known that water penetrates the PA films, causing swelling and increasing the diffusion of migrants. Moreover, in some cases, there was a greater migration of ε-caprolactam in the fatty simulant. These results can be attributed to the concept that the polymeric matrix tends to absorb the oil (which can act as a plasticizer), resulting in structural changes in the film and consequently favoring the migration of low molecular weight compounds to the fatty simulant, as discussed by Galotto et al. (2010).

However, the values obtained from migration of ε-caprolactam both for the control samples and for the processed samples of the two packaging materials and in contact with the different simulants are less than 15 mg kg^{-1} of simulant, and the values are thus accepted by RDC No. 56/2012 from ANVISA (Brazil, 2012) and by the EU Regulation No. 10/2011 (European-Commission, 2011).

Furthermore, according to the RDC No. 51/2010 from ANVISA (Brazil, 2010), packaging materials submitted to migration tests must remain in contact with the food simulant, ensuring that it only contacts the parts of the packaging that are actually in contact with the food, in order to represent the real conditions of contact with the food. Emphasize that this study was carried out under these conditions, being an important feature for multilayer packaging materials. In addition, the condition of time and temperature to which the packaging is subjected under the actual conditions of use must be considered, highlighting that the storage condition of 40 °C/10 days, which was employed in our study, corresponds to the most extreme predictable conditions regarding

the contact between food and the packaging material. That is, under less severe conditions, the packaging materials in this study will very likely result in lower migration values of ε-caprolactam in the evaluated food simulants.

4. Conclusions

Based on the results, can conclude that the processing and conditioning conditions to which the studied samples were submitted result in an overall migration below the limit of quantification ($\leq$2.33 mg dm^{-2}) for all samples. The specific migration of ε-caprolactam was influenced by the type of food simulant, packaging material, processing conditions employed, and temperature/time of contact with the food simulant.

The migration of ε-caprolactam to the different food simulants immediately after the different processing method was higher when processed under atmospheric pressure and high-temperature (0.1 MPa/90 °C/10 min) than when processed under high pressure (600 MPa). In other words, high-pressure processing had less influence on migration than high-temperature.

Samples processed by high-pressure at 600 MPa, 25 °C and 90 °C/10 min and conditioned at 40 °C/10 days reduced or kept the results of specific migration of ε-caprolactam in the different food simulants evaluated (acid, aqueous, and fatty) equal to the control, both for LDPE/PA/LDPE packaging and for PET/LDPE/PA/EVOH/PA/LDPE packaging. The highest results of specific migration of ε-caprolactam were for control packages (conditioned at 40 °C/10 days) of LDPE/PA/LDPE (2.58 mg kg^{-1} of simulant). The LDPE/PA/LDPE packaging showed migration values higher than the PET/LDPE/PA/EVOH/PA/LDPE packaging. However, all evaluated samples and conditions complied with the Brazilian and European Union legislation.

CRediT authorship contribution statement

Luís Marangoni: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Writing - original draft, Writing - review & editing. **Mary Ângela Fávaro Perez:** Formal analysis, Investigation, Methodology, Writing - review & editing. **Caroline Donadon Torres:** Formal analysis, Investigation, Methodology, Writing - review & editing. **Marcelo Cristianini:** Conceptualization, Methodology, Funding acquisition, Writing - review & editing. **Paulo Henrique Massaharu Kiyataka:** Formal analysis, Investigation, Methodology, Writing - review & editing. **Aline Cristina Albino:** Formal analysis, Investigation, Methodology. **Marisa Padula:** Conceptualization, Funding acquisition, Supervision, Writing - review & editing. **Carlos Alberto Rodrigues Anjos:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors report no declarations of interest.

Acknowledgements

The authors acknowledge the São Paulo Research Foundation (FAPESP) for the financial support (grant #2018/05588-0), the industries that supplied the packaging materials, the Emerging Technologies Laboratory – FEA/UNICAMP, the Chemistry and Chromatography Laboratory – CETEA/ITAL, and *Espaço da Escrita – Coordenadoria Geral da Universidade – UNICAMP* – for the language services provided. The author Luís Marangoni Júnior thanks the National Council for Scientific and Technological Development (CNPq) (grant #140793/2017-8) for the granted PhD scholarship. This study was partly financed by the Coordination for the Improvement of Higher Education Personnel – Brazil (CAPES) – Financial Code 001.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.fpsl.2020.100576.

References

ABNT NBR ISO/IEC 17025. (2017). *Orientações gerais sobre os requisitos da ABNT NBR ISO/IEC 17025*, 2017.

Araújo, H. P., Felix, J. S., Manzoli, E., Padula, M., & Monteiro, M. (2008). Effects of g -irradiation on caprolactam level from multilayer PA-6 films for food packaging : Development and validation of a gas chromatographic method. *Radiation Physics and Chemistry, 77*, 913–917. https://doi.org/10.1016/j.radphyschem.2008.03.001

Ayvaz, H., Balasubramaniam, V. M., & Koutchma, T. (2016). High pressure effects onpackaging materials. In V. M. Balasubramaniam, G. V. Barbosa-Cánovas, & H. L. M. Lelieveld (Eds.), *High pressure processing of food: Principles, technologyand applications* (pp. 73–93). New York: Springer.

Blanco-Zubiaguirre, L., Zabaleta, I., Usobiaga, A., Prieto, A., Olivares, M., Zuloaga, O., & Elizalde, M. P. (2020). Target and suspect screening of substances liable to migrate from food contact paper and cardboard materials using liquid chromatography-high resolution tandem mass spectrometry. *Talanta, 208*, Article 120394. https://doi.org/10.1016/j.talanta.2019.120394

Bomfim, M. V. J., Zamith, H. P. S., & Abrantes, S. M. P. (2011). Migration of 3 -caprolactam residues in packaging intended for contact with fatty foods. *Food Control, 22*, 681–684. https://doi.org/10.1016/j.foodcont.2010.09.017

Brazil. (1999). *Resolution RDC n 105 from 19 de May 1999. Providess technical regulations on general provisions for packaging and plastic equipment for food contact* (Diário Oficial da República Federativa do Brasil), Brasília, DF, 16 mar. 2000. Seção 1.

Brazil. (2010). *Resolution RDC n 51 from 26 November 2010. Provides for migration on materials, packaging and plastic equipment intended to come into contact with food* (Diário Oficial da República Federativa do Brasil), Brasília, DF, n.244, 22 dez. 2010. Seção 1, p. 75.

Brazil. (2012). *Resolution RDC n 56 from 16 November 2012. State on positive list of monomers, other starting substances and authorized polymers to development of packaging and plastic equipment in contact with foodstuffs* (Diário Oficial [da] República Federativa do Brasil, Seção 1, Brasília, DF).

Brazil. (2019). *Resolution RDC n 326 from 03 December 2019. State on positive list of monomers, other starting substances and authorized polymers to development of packaging and plastic equipment in contact with foodstuffs* (Diário Oficial [da] República Federativa do Brasil, Seção 1, Brasília, DF).

Bustos, J., Sendon, R., Sanchez, J. J., Paseiro, P., & Cirugeda, M. E. (2009). Migration of epsilon-caprolactam from nylon cooking utensils: Validation of a liquid chromatography-ultraviolet detection method. *European Food Research and Technology, 230*(2), 303–313. https://doi.org/10.1007/s00217-009-1171-4

Caner, C., & Harte, B. (2005). Effect of high-pressure processing on the migration of antioxidant Irganox 1076 from polypropylene film into a food simulant. *Journal of the Science of Food and Agriculture, 85*, 39–46. https://doi.org/10.1002/jsfa.1935

CEN/TS 13130-16. (2005). *European commitee for standardization. Materials and articles in contact with foodstuffs - Plastics substance subject to limitation - Part 16: Determination of caprolactam and caprolactam salt in food simulants*. February (pp. 1–16).

EN 1186-1. (2002). *Materials and articles in contact with foodstuffs. Plastic. Part 1: Guide to the selection of conditions and test methods for overall migration*.

EN 1186-1189. (2002). *Materials and articles in contact with foodstuffs. Plastic. Part 9: Test methods for overall migration into aqueous food simulants by article filling*.

European-Commission. (2011). Regulation n. 10/2011 on plastic materials and articles intended to come into contact with food. *Official Journal of the European Union, L12*, 1–89.

Félix, J. S., Padula, M., Manzoli, J. E., & Monteiro, M. (2006). Desenvolvimento e validação de método analítico para determinação de e-caprolactama em simulante de alimentos gordurosos. *Alimentos e Nutrição (UNESP), 17*, 329–335.

Félix, J. S., Manzoli, J. E., Padula, M., & Monteiro, M. (2014). Evaluation of different conditions of contact for caprolactam migration from multilayer polyamide films into food simulants. *Packaging Technology and Science, 27*, 457–466. https://doi.org/10.1002/pts.2046

Galotto, M. J., Ulloa, P., Escobar, R., Guarda, A., Gavara, R., & Miltz, J. (2010). Effect of high-pressure food processing on the mass transfer properties of selected packaging materials. *Packaging Technology and Science, 23*, 253–266. https://doi.org/10.1002/pts.893

Guillard, V., Mauricio-Iglesias, M., & Gontard, N. (2010). Effect of novel food processing methods on packaging: Structure, composition, and migration properties. *Critical Reviews in Food Science and Nutrition, 50*(10), 969–988. https://doi.org/10.1080/10408390903001768

Heimrich, M., Nickl, H., Bönsch, M., & Simat, T. J. (2015). Migration of cyclic monomer and oligomers from polyamide 6 and 66 food contact materials into food and food simulants: Direct food contact. *Packaging Technology and Science, 28*, 123–139. https://doi.org/10.1002/pts.2094

Hernández-Hernández, H. M., Moreno-Vilet, L., & Villanueva-Rodríguez, S. J. (2019). Current status of emerging food processing technologies in Latin America: Novel non-thermal processing. *Innovative Food Science and Emerging Technologies, 58* (September), Article 102233. https://doi.org/10.1016/j.ifset.2019.102233

Ibarra, V. G., De Quirós, A. R. B., Losada, P. P., & Sendón, R. (2019). Non-target analysis of intentionally and non intentionally added substances from plastic packaging materials and their migration into food simulants. *Food Packaging and Shelf Life, 21* (May), Article 100325. https://doi.org/10.1016/j.fpsl.2019.100325

Koutchma, T., Song, Y., Setikaite, I., Juliano, P., Barbosa-Cánovas, G. V., Dunne, C. P., & Patazca, E. (2010). Packaging evaluation for high-pressure high-temperature sterilization of shelf-stable foods. *Journal of Food Process Engineering, 33*(6), 1097–1114. https://doi.org/10.1111/j.1745-4530.2008.00328.x

Lai, C., Chen, S., Chen, M., Chen, H., Hsiao, H., Liu, L., & Chen, C. (2019). Preparation and characterization of heterocyclic polyamide 6 (PA 6) with high transparencies and low hygroscopicities. *Journal of Molecular Structure, 1175*, 836–843. https://doi.org/10.1016/j.molstruc.2018.08.032

Lambert, Y., Demazeau, G., Largeteau, A., Bouvier, J., Laborde-Croubit, S., & Cabannes, M. (2000). Packaging for high-pressure treatments in the food industry. *Packaging Technology and Science, 13*, 63–71. https://doi.org/10.1002/1099-1522(200003/04)13:2<63::AID-PTS495>3.0.CO;2-6

Marangoni, L., Júnior, Cristianini, M., Padula, M., & Anjos, C. A. R. (2019). Effect of high-pressure processing on characteristics of flexible packaging for foods and beverages. *Food Research International, 119*(August 2018), 920–930. https://doi.org/10.1016/j.foodres.2018.10.078

Marangoni, L., Júnior, Alves, R. M. V., Moreira, C. Q., Cristianini, M., Padula, M., & Anjos, C. A. R. (2020). High-pressure processing effects on the barrier properties of flexible packaging materials. *Journal of Food Processing and Preservation, 00*, Article e14865. https://doi.org/10.1111/jfpp.14865

Marangoni, L., Júnior, Cristianini, M., & Anjos, C. A. R. (2020). Packaging aspects for processing and quality of foods treated by pulsed light. *Journal of Food Processing and Preservation, 00*, Article e14902. https://doi.org/10.1111/jfpp.14902

Marangoni, L., Júnior, De Oliveira, L. M. De., Bócoli, P. F. J., Cristianini, M., Padula, M., & Anjos, C. A. R. (2020). Morphological, thermal and mechanical properties of polyamide and ethylene vinyl alcohol multilayer flexible packaging after high-pressure processing. *Journal of Food Engineering, 276*(October 2019). https://doi.org/10.1016/j.jfoodeng.2020.109913

Marangoni, L., Júnior, Oliveira, L. M., Dantas, F. B. H., Cristianini, M., Padula, M., & Anjos, C. A. R. (2020). Influence of high-pressure processing on morphological, thermal and mechanical properties of retort and metallized flexible packaging. *Journal of Food Engineering, 273*(August 2019). https://doi.org/10.1016/j.jfoodeng.2019.109812

Mccombie, G., Biedermann, M., & Authority, C. (2019). Migration from food contact materials. In *Encyclopedia of food chemistry* (Vol. 1). Elsevier. https://doi.org/10.1016/B978-0-08-100596-5.21830-1

Padula, M., Saorin, F., Cofcewicz, G., Perez, M. A. F., Soares, B. M. C., Felipe, F. R. S., … Bonato, B. (2016). Influence of high pressure processing (hpp) on packaging migration potential. In *International Symposium on Food Packaging*.

Prakasam, M., & Largeteau, A. (2017). 11 - Flexible packaging for nonthermal decontamination by high hydrostatic pressure. *Food packaging*. Elsevier Inc.. https://doi.org/10.1016/B978-0-12-804302-8/00011-X

Robertson, G. L. (2013). *Food packaging: Principles and practice* (3rd ed.). Boca Raton: CRCPress.

Song, Y. S. (2014). Effect of high pressure processing on migration characteristics in polymer films. In *ACS Symposium Series*.

Song, H. J., Chang, Y., Lyu, J. S., et al. (2018). Migration study of caprolactam from polyamide 6 sheets into food simulants. *Food Science and Biotechnology, 27*, 1685–1689. https://doi.org/10.1007/s10068-018-0403-4

Stoffers, N. H., Brandsch, R., Bradley, E. L., Cooper, I., Dekker, M., Störmer, A., & Franz, R. (2005). Feasibility study for the development of certified reference materials for specific migration testing. Part 2: Estimation of diffusion parameters and comparison of experimental and predicted data. *Food Additives and Contaminants, 22*(2), 173–184. https://doi.org/10.1080/02652030400028076