

Effect of Gamma and X-ray Irradiation on Polymers Commonly Used in Healthcare Products

Philip Roxby, Hervé Michel, Céline Huart, and Samuel Dorey

Abstract

Synthetic organic polymers commonly are used in the construction of healthcare product and medical device components. Medical devices often are sterilized to ensure that they are free from viable microorganisms. A common technique to achieve this is using ionizing radiation, usually gamma. A trend exists in industrial sterilization to supplement gamma with alternative accelerator technologies (e.g., X-ray). In the current work, studies were performed to characterize polymer modifications caused by gamma and X-ray sterilization processes and to assess the comparative equivalency. The studies were developed to evaluate two key process parameters: dose and dose rate. Three commonly used polymers were selected: high-density polyethylene, low-density polyethylene, and polypropylene. Four grades of each family were chosen. The dose assessment involved sample exposures to both gamma and X-ray irradiation at two dose levels (30 and 55 kGy). All other processing conditions, including dose rate, were controlled at standard processing levels akin to each sterilization technology. The dose rate assessment expanded on each dose level by introducing two additional dose rate parameters. Subsequent laboratory testing used techniques to characterize physico-chemical properties of the polymers to ascertain equivalency across test groups. Initial results indicated positive levels of equivalency between gamma and X-ray irradiation.

As demand for the manufacturing of single-use healthcare and biopharmaceutical products has grown, the need for sterilization capacity also has increased. Currently gamma radiation sterilization accounts for slightly more than 80% of the ionizing radiation sterilization market for single-use medical products, with the other two primary technologies being X-ray and electron beam.¹

In recent years, X-ray irradiation facilities have become more plentiful. They not only

support gamma irradiation as a viable alternative but can also provide advantages in terms of economics, environmental impact, and polymer acceptability.² Material impact assessments often are performed when transferring a product from one sterilization technology to another. In addition to these assessments, other tests may be conducted to verify product functionality and regulatory compliance. Tests such as these are of considerable importance in confirming equivalence and participation in regulatory pathways, including the Food and Drug Administration's Radiation Sterilization Master File Pilot Program for premarket approval devices.³

The current study sought to quantify polymer modification and to assess equivalency between both gamma and X-ray sterilization processes across various doses and dose rates. Tests were conducted at a molecular and macromolecular level on samples treated with various processing conditions, in order to quantify the change in intrinsic properties and to subsequently conduct equivalency tests on the data sets.

Materials and Methods

Samples

To ensure this study was industry relevant, the sample materials chosen were of grades used in components that are found in various products (provided by Sartorius, Aubagne, France). A total of 12 polymer grades were tested. Ten were tested in molded component form, and two were tested as molded dogbones. Samples were not sterilized prior to the study.

The three material families selected were:

1. High-density polyethylene (HDPE): Identified as HPDE-1, HPDE-2, HPDE-3, and HPDE-4, with density values ranging from 0.947 to 0.962 g/cm³ and melt flow index [MFI] ranging from 6 to 26 g/10 min at 190°C/2.16 kg.
2. Linear low-density polyethylene (LDPE):

Philip Roxby, BEng, is a senior technical manager at STERIS in Galway, Ireland. Email: philip_roxby@steris.com **Corresponding author**

Hervé Michel, MSc, is a director of radiation technology at STERIS in Däniken, Switzerland. Email: herve_michel@steris.com

Céline Huart is a materials and irradiations intern at Sartorius in Aubagne, France. Email: celine_huart@sartorius.com

Samuel Dorey, PhD, is a principal scientist in materials and irradiations at Sartorius in Aubagne, France. Email: samuel.dorey@sartorius.com

Identified as LDPE-1 and LDPE-2, with density values of 0.925 and 0.920 g/cm³, respectively, and MFI of 2 and 25 g/10 min, respectively, at 190°C/2.16 kg.

LDPE: Identified as LDPE-3 and LDPE-4, with density values of 0.923 g/cm³ (for both) and MFI of 1.1 and 20 g/10 min, respectively, at 190°C/2.16 kg.

3. Polypropylene (PP): Identified as PP-1, PP-2, PP-3, and PP-4, with density values of 0.9 g/cm³ and MFI ranging from 4 to 35 g/10 min at 230°C/2.16 kg.

Irradiation

Dose assessment. Each of the aforementioned polymer grades were included in the assessment of dose level. Two typical industrial target dose levels (30 and 55 kGy) were chosen, bracketing the minimal and maximal routine doses. Samples were irradiated in continuous and incremental modes to mimic routine sterilization

processing conditions. Dose rate was maintained at a standard processing level akin to each irradiation technology. This resulted in an X-ray average dose rate of 34 kGy/h and gamma average dose rate of 11 kGy/h at each dose level. The average irradiation temperature was recorded during each condition. Both X-ray and gamma processing for this portion of the study was performed at the STERIS facility in Däniken, Switzerland. Table 1 provides details of each test condition.

Dose rate assessment. To assess any potential dose rate effect, one material grade from each polymer family was studied. This assessment used two distinct dose rate conditions. Due to the contrasting radiation source technologies, X-ray was conducted at 10 and 80 kGy/h and gamma was conducted at 1 and 10 kGy/h. These dose rates were paired with the same industrial target dose levels (30 and 55 kGy)

Technology	Target Dose (kGy)	Actual Average Dose (kGy)	Average Dose Rate (kGy/h)	STERIS Location	Average Irradiation Temperature (°C)	Materials Tested
Co-60	30	29.9	11	Däniken, Switzerland	37.5	All HDPE, LDPE, and PP
Co-60	55	54.7	11	Däniken, Switzerland	37.5	All HDPE, LDPE, and PP
X-ray 7 MeV	30	29.3	34	Däniken, Switzerland	35	All HDPE, LDPE, and PP
X-ray 7 MeV	55	55.2	34	Däniken, Switzerland	35	All HDPE, LDPE, and PP
Co-60	30	29.8	1	Bradford, UK	<27.5	HDPE-1, LDPE-1, and PP-4 only
Co-60	30	29.5	10	Bradford, UK	<27.5	HDPE-1, LDPE-1, and PP-4 only
Co-60	55	56.0	1	Bradford, UK	<27.5	HDPE-1, LDPE-1, and PP-4 only
Co-60	55	55.0	10	Bradford, UK	<27.5	HDPE-1, LDPE-1, and PP-4 only
X-ray 7 MeV	30	31.4	10	Däniken, Switzerland	31	HDPE-1, LDPE-1, and PP-4 only
X-ray 7 MeV	30	30.5	80	Däniken, Switzerland	38	HDPE-1, LDPE-1, and PP-4 only
X-ray 7 MeV	55	55.5	10	Däniken, Switzerland	33	HDPE-1, LDPE-1, and PP-4 only
X-ray 7 MeV	55	56.8	80	Däniken, Switzerland	40	HDPE-1, LDPE-1, and PP-4 only

Table 1. Summary of study conditions and processing location. Abbreviations used: Co-60, cobalt-60; HDPE, high-density polyethylene; LDPE, low-density polyethylene; PP, polypropylene.

as previously evaluated. Static mode was used to ensure samples were treated at a constant dose rate throughout the entire process. The average irradiation temperature was recorded during each condition, with the exclusion of the gamma irradiation, which was performed in a temperature-controlled treatment room (at 27.5°C). X-ray processing was performed at the STERIS facility in Däniken, Switzerland, while gamma processing was performed at the STERIS Radiation Technology Centre in Bradford, UK. Table 1 provides details of each test condition.

Characterization methods

The three test methods described below were used to characterize the physico-chemical properties of the polymer samples to ascertain equivalency across test groups. These are established, industry standard techniques used to assess healthcare products.⁴

Differential scanning calorimetry. Differential scanning calorimetry (DSC) testing was used to identify the impact of sterilization on the melting temperature (T_m) of each sample. The method was derived from ISO 11357-1:2016⁵ and conducted on a single-furnace, heat flux differential scanning calorimeter (DSC 4000; PerkinElmer, Waltham, MA) with an Indium calibration standard. Maximum temperature (T_{max}) values were established (HDPE 160°C, LDPE 150°C, and PP 190°C) by conducting initial probe tests and increasing T_m by 30°C in each case. The heating profile used for each test consisted of two heating and cooling cycles as described in Table 2. The thermal transitions for each material, namely T_m for this study, were calculated directly by the DSC software. The T_m values were the average of three replicates from the first and second heating cycles.

Attenuated total reflectance Fourier transform infrared spectroscopy. Attenuated total reflectance Fourier transform infrared (ATR-FTIR) spectroscopy was used to collect spectral data from each test sample. This enabled a comparison of each spectral fingerprint to identify variations caused by the sterilization conditions. The spectral data analysis involved checks for the appearance or disappearance of peaks and quantifying peak shifts using principal component analysis (PCA). An FTIR spectrometer (Spectrum FTIR; PerkinElmer) was used to record spectra, with 64 scans per sample cycle at 4 cm⁻¹ resolution from 650 to 4,000 cm⁻¹. ATR was used as the system operation mode, and a polystyrene calibration material was utilized.

Gel permeation chromatography. Gel permeation chromatography (GPC) was performed to quantify any change in molecular weight distribution of the samples to assess the impact caused by sterilization conditions. A GPC system (EcoSEC HT GPC; Tosoh Bioscience, Tokyo, Japan) with gel column (300 mm × 7.5 mm) was configured with a narrow calibration standard (TSKGel Standard Polystyrene; Tosoh Bioscience) with a concentration of 2.0 mg/mL. Standard curves were generated and used to calculate the weight average molecular weight (Mw), number average molecular weight (Mn), and polydispersity index. Tests were conducted with an oven temperature of 145°C using high-performance liquid chromatography-grade trichlorobenzene at a flow rate of 1.0 mL/min, concentration of 2.0 mg/mL (16 mg/8 mL), and injection size of 300 mL.

Equivalence and Equivalency Criteria

To establish equivalency criteria for the DSC testing, an equivalence testing approach was

Step	Action
1	Heat from -20°C to T_{max} at 10°C/min
2	Maintain T_{max} isothermally for 5 min
3	Cool down to -20°C at 10°C/min
4	Maintain -20°C isothermally for 5 min
5	Heat from -20°C to T_{max} at 10°C/min

Table 2. Heating profile. Abbreviation used: T_{max} , maximum temperature.

used that adopted the univariate two-one-sided t test (TOST) method and applied a maximum limit to the difference in means. The equivalence acceptance criteria were determined from the maximum deviations observed in randomized, replicate measurements drawn from a separate pool of DSC data from previous repeatability studies, across multiple samples (Table 3). The three-sigma approach then was used to determine equivalency criteria.⁶

Statistical evaluation could not provide suitable criteria for ATR-FTIR spectroscopy testing; therefore, conclusions were drawn using PCA (Table 3). The goal of a simple PCA is to establish an interpretable solution.⁷

Molecular weight equivalency criteria were tentatively provided. This was due to the intrinsic uncertainty associated with the results, potentially due to a high proportion of insoluble polymer fraction.

Equivalence tests (TOST method) were carried out with Minitab 2020.1.1 software (Minitab, State College, PA). Equivalence tests were performed on each material at an equivalent dose (0, 30, or 55 kGy) and equivalent dose rate (routine, high, or low) across each irradiation technology (gamma or X-ray).

PCA

PCA is a technique for reducing the dimensionality of datasets, thereby increasing interpretability while minimizing information loss.⁸ This is achieved by creating new uncorrelated variables that successively maximize variance. The main systematic variation in the data set is given by the principal component (PC). The common characteris-

tics of all spectra are modeled with one or several $PC_{1,2,\dots,n}$. PCA is used as an exploratory tool for data analysis. For this study, this analysis was conducted using SIMCA 17 software (Sartorius). Both the variations in intensity and the shift of the ATR-FTIR peaks were investigated relative to the sterilization parameters. For each PCA, the spectra were adjusted using the asymmetric least squares (AsLS) baseline correction approach and/or the standard normal variate normalization approach. In cases in which the AsLS distorted the spectra by creating artificial peaks at approximately 3,050 and 2,750 cm^{-1} , the data were omitted from the material assessment.

Results and Discussion

The signature behaviors of the polymers were studied in relation to molecular structure at doses of 0, 30, and 55 kGy, with various irradiation conditions bracketing routine sterilization processes. For clarity, the results have been separated into subsections according to each material family: HDPE, LDPE, and PP. The results of each experiment are detailed below and a conclusion on each material family has been given.

HDPE

DSC results (HDPE). The mean T_m for each HDPE grade was calculated and plotted (Figure 1). These data were checked for equivalency, and T_m equivalency was confirmed across both X-ray- and gamma-irradiated samples, regardless of dose and dose rate. All P values for the datasets were confirmed to be less than 0.05. Onset temperature (T_{on}) for each HDPE

Characterization Method	Equivalency Criteria
DSC	$-5^\circ\text{C} < T_{m \text{ X-ray}} - T_{m \text{ gamma}} < 0^\circ\text{C}$ or $0^\circ\text{C} < T_{m \text{ X-ray}} - T_{m \text{ gamma}} < 5^\circ\text{C}$
	$-5^\circ\text{C} < T_{on \text{ X-ray}} - T_{on \text{ gamma}} < 0^\circ\text{C}$ or $0^\circ\text{C} < T_{on \text{ X-ray}} - T_{on \text{ gamma}} < 5^\circ\text{C}$
ATR-FTIR	No appearance of peak linked to assessed materials.
	No disappearance of peak linked to assessed materials.
	Peak shift $< 8 \text{ cm}^{-1}$ linked to assessed materials.
GPC	Due to method variation, no criteria currently exist. Criteria will be proposed as an output of this study.

Table 3. Equivalency criteria for each characterization method. Abbreviations used: ATR-FTIR, attenuated total reflectance Fourier transform infrared spectroscopy; DSC, differential scanning calorimetry; GPC, gel permeation chromatography; T_m , melting temperature; T_{on} , onset temperature.

sample showed a similar trend. No change was observed from nonirradiated materials to irradiated materials.

ATR-FTIR results (HDPE). Examples of HDPE ATR-FTIR spectra are shown in Figure 2. The presence of a spectra overlap is apparent. Peaks were identified and assigned (Table 4). Separate studies indicated that gamma irradiation at high doses (>100 kGy) can result in changes in sample ATR-FTIR spectra.⁹ This is displayed in two main zones: carboxylic acids (1,760–1,660 cm^{-1}) and unsaturated groups (975–875 cm^{-1}). The appearance of a signal change is also expected at this dose level.⁸ The spectra data gathered in this study showed no observable peaks in these zones. There was no peak appearance or disappearance on the spectra, and there was no shift of the main peaks regardless of irradiation condition or radiation source. This was also the case across the HDPE family.

The PCA did not reveal any change with respect to dose, dose rate, or radiation source. The impact of the absorbed dose on the polymer was homogeneous, with an overlap between the 30-kGy and 50-kGy irradiated groups. Homogeneity was also apparent on dose rate samples and across both radiation sources for all materials.

Significant crosslinking and chain scission events were expected to occur in PEs,¹⁰ though no significant changes were observed in these HDPE ATR-FTIR signals. No trends were observed for samples exposed to X-ray irradiation compared with those exposed to gamma irradiation. Further, no trends were observed among processing conditions.

GPC results (HDPE). Common commercial grades of PE have an Mn in the order of 10,000 to 40,000 Da and a corresponding Mw in the range of 50,000 to 300,000 Da.¹⁴ A decrease in the average molecular weight and the broadening of the molecular weight distribution can provide initial evidence of the degradation of a polymer after different stresses.¹⁵ In contrast, increased molecular weight can result in an elevated tensile strength, impact toughness, creep resistance, and T_m .¹⁶ Mn and Mw values for the HDPE-1 samples irradiated in conditions listed in Table 1 were plotted (Figure 3, left). Irradiated HDPE tends to cross-link as molecular

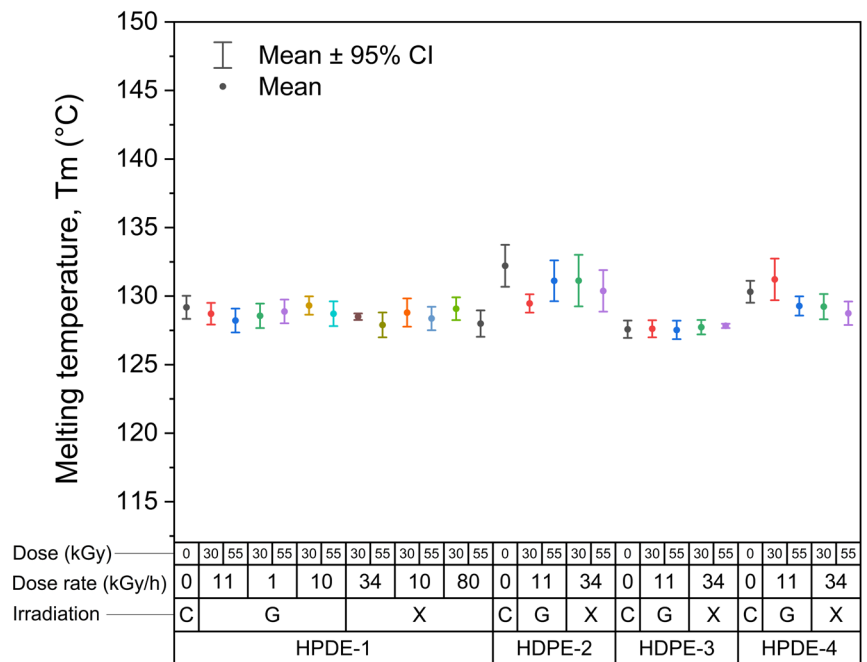


Figure 1. Melting temperature (T_m ; internal plots) be measured for each high-density polyethylene (HDPE) sample for each processing condition. Abbreviations used: C, control; CI, confidence interval; G, gamma; X, X-ray.

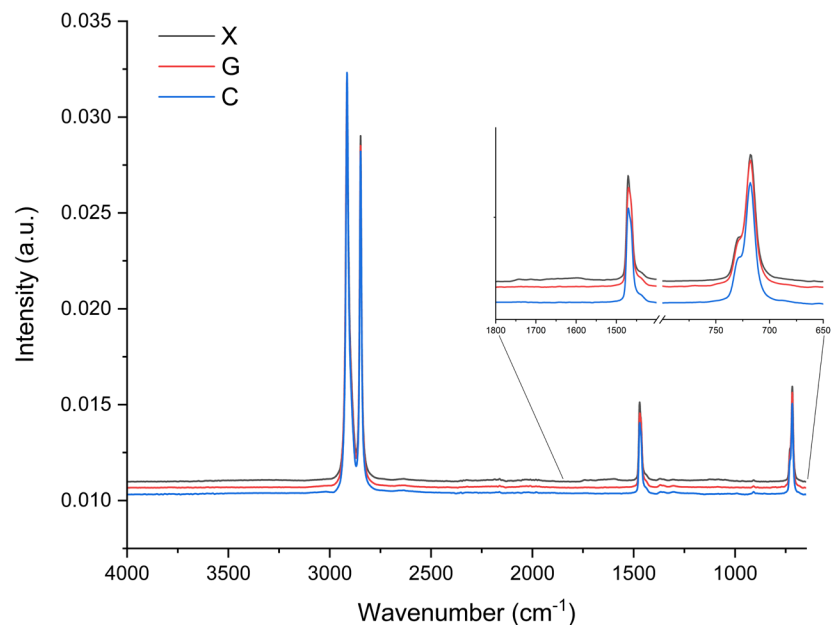


Figure 2. Attenuated total reflectance Fourier transform infrared spectroscopy spectra for high-density polyethylene (HDPE)-3 material irradiated at 30 kGy. Abbreviations used: C, control; G, gamma; X, X-ray.

weight increases. This phenomenon is accentuated as dose is increased.

No differences in the Mw results were observed for X-ray and gamma at the 30-kGy dose across all dose rates. In addition, no differences in the Mw results were seen for X-ray at the 55k-Gy dose and 80-kGy/h rate and gamma at the 55-kGy dose and 11-kGy/h

Infrared Wavenumber (cm ⁻¹)	Functional Group	Potential Irradiation-Induced Peaks in			
		HDPE, Linear LDPE	Polyethylene	PP	PP
2,970	CH ₃ asymmetric stretching	—	NA	X ^a	NA
2,920	CH ₂ asymmetric stretching	X	NA	X	NA
2,850	CH ₂ symmetric stretching	X	NA	X	NA
1,760–1,660	Carboxylic acid zone	—	Yes*	—	Yes†
1,450	Bending deformation	X	NA	X	NA
1,350	CH ₃ symmetric deformation	X	NA	X	NA
1,165	Ester group	—	NA	—	Yes†
1,160	Wagging CH, rocking CH ₃	—	NA	X	NA
995	Rocking CH ₃ , stretching C–C	—	NA	X	NA
973	Rocking CH ₃ , stretching C–C	—	NA	X	NA
975–875, 890	Unsaturated group zone (R ₁ –CH = CH–R ₂)	—	Yes*	—	NA
975–875, 964	Unsaturated group zone (R ₁ –CH–CH ₂)	—	Yes*	—	NA
975–875, 908	Unsaturated group zone (R ₁ R ₂ C = CH ₂)	—	Yes*	—	NA
840	Rocking C–H	—	NA	X	NA
810	Stretching C–C	—	NA	X	NA
730	Rocking deformation of CH ₂ in the crystalline part	X	NA	—	NA
720	Rocking deformation of CH ₂ in the amorphous part	X	NA	—	NA

Table 4. Attenuated total reflectance Fourier transform infrared spectroscopy (ATR-FTIR) peak assignment^{8–12} for high-density polyethylene (HDPE), linear low-density polyethylene (LDPE), and polypropylene (PP) when materials were not irradiated. Only main peaks for PP were considered. Expected peaks when materials were irradiated at doses >100 kGy are also given. X indicates peak present in polymer family, and — indicates peak not present in pristine polymer. *A change in the signal may occur due to gamma irradiation with high doses (>100 kGy).¹⁰ †Potential oxidation peaks observed in PP materials.¹³ Abbreviations used: C, carbon; CH₂, methylene group; CH₃, methyl group; H, hydrogen; NA, not applicable; R₁ and R₂, side chains with number of carbon ≥1.

rate. The Mw results were equivalent for all 55-kGy replicates in the X-ray irradiation series regardless of the dose rate. The Mw gamma series exhibited variation, with two repetitions at 55 kGy with the respective dose rate of 10 and 11 kGy/h.

In parallel, all Mn results for gamma and X-ray were equivalent. Mn and Mw for the irradiated HDPE-2 were plotted in Figure 3 (right) and presented no evolution for any irradiation conditions listed in Table 1. The HPDE-2 samples presented the highest density and the highest MFI in that study,

though it was not clear if the latter was influenced by the output of the irradiation.

Neither a shift of thermal properties nor a broadening of GPC curves was observed (not presented in this article), indicating that the extent of these events in our testing results was minimal. As a result, the reproducibility within the Mw/Mn series also was low (up to a factor of 2). Therefore, molecular weight measurements showed no degradation attributed to either irradiation technology or processing parameters. Molecular weight measurements indicated a tendency of

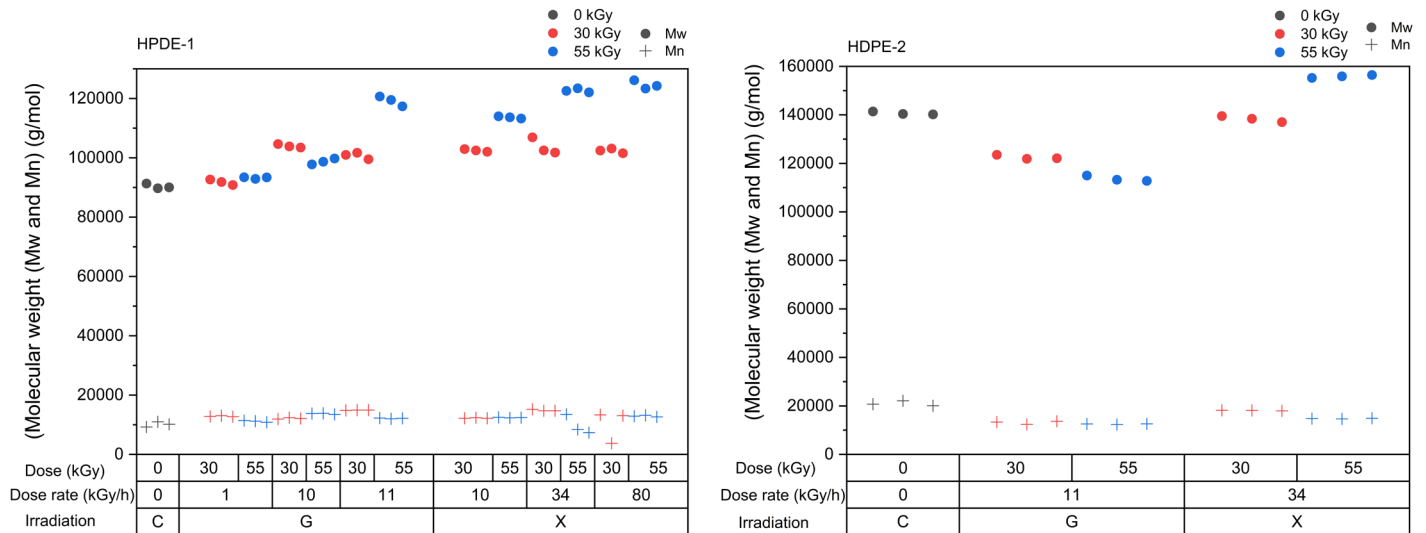


Figure 3. Weight average molecular weight (Mw) and number average molecular weight (Mn) for high-density polyethylene (HDPE)-1 (*left*) and HDPE-2 (*right*). Three replicates are plotted. Abbreviations used: C, control; G, gamma; X, X-ray.

weight gain for HDPE, and the quantitative levels were more akin to experimental and analytical variability.

LDPE

DSC results (LDPE). The range of T_m values obtained for the LDPE family were between 110°C and 125°C. T_m for each LDPE grade was shown to be equivalent and independent of the radiation source, dose rate, and dose. This is also the case for the other material families and is in alignment with similar studies.^{17,18} T_{on} also followed the same trend. TOST data showed that for X-ray- and gamma-irradiated samples, T_m values were within the equivalence range and therefore were considered equivalent for each condition ($P_{TOST} < 0.05$).

ATR-FTIR results (LDPE). The ATR-FTIR spectra for the LDPE family exhibited peaks similar to the HDPE family. There was an overlap of spectra on irradiated samples. There was no peak appearance or disappearance on the spectra, and there was no shift of the main peaks. No new peaks were observed in both the carboxylic acid zone and the unsaturated groups zone. PCA showed that major variations were due to a baseline shift, and no changes due to dose, dose rate, or irradiation source were identified. Although significant crosslinking and chain-splitting events were expected in PE,¹⁰ no significant change to the LDPE chains were detected under these experimental conditions. In

addition, no impact occurred from the irradiation technology and treatment condition.

GPC results (LDPE). Comparing nonirradiated and irradiated samples, a tendency to cross-link as the molecular weight increased. This phenomenon was accentuated with increasing dose.

Of note, neither a shift in thermal properties nor a broadening of GPC curves was observed. Further, part-to-part variation was noted on occasion. This suggested that the cause of modification may not be limited to dose but also could result from variability within the method.

PP

DSC results (PP). As with the other material families, T_m was shown to be equivalent across the PP family regardless of the radiation source, dose rate, and dose (Figure 4). T_{on} followed the same trend (results not shown). Equivalency tests confirmed that the T_m values for each processing condition of X-ray- and gamma-irradiated samples were equivalent. All P values were less than 0.05. For PP, a decrease of T_m was observed across both radiation sources following irradiation of materials.

ATR-FTIR results (PP). Figure 5 shows an overlap of a PP-4 ATR-FTIR spectra. No peak appearance or disappearance occurred, and no shift of peaks was present. All peaks were

assigned in Table 4. The carboxylic acid zone was also unaffected. These observations were valid across the PP family. PCA showed that no change was attributed to dose, dose rate, or irradiation source. Again, neither the irradiation technology nor the treatment conditions had an effect.

GPC results (PP). As shown in Figure 6 (left), Mw and Mn for PP-1 decreased as irradiation dose increased. PP-3 exhibited the same trend. For PP-2, Figure 6 (right) shows Mw decreasing and Mn slightly increasing with increasing irradiation doses. This indicated a tendency for chain scission following irradiation of samples across both X-ray and gamma. No dose rate effect was observed in any case. A dose effect tendency was observed, with increased chain breaking noted at 55 kGy compared with 30 kGy. In contrast, PP-4 presented an increase of Mw and Mn.

Lower molecular weights tended to reduce the material T_m and increase the ease of processing. Similarly, a broader molecular weight distribution decreased the T_m . Broad molecular weight distribution represented polymers with many shorter molecules that are not as entangled and therefore melt at lower temperatures.¹⁵ Neither a shift of thermal properties nor a broadening of GPC curves was observed (not shown), indicating that the extent of these events was weak.

Reproducibility was assessed on two PP-1 components (labeled P1 and P4 in Figure 6, left) that underwent the same irradiation conditions. Both Mw and Mn data sets displayed an average difference of approximately 30% for Mn and approximately 20% for Mw. Of important note, a skin effect potentially occurred with PP samples in this study (i.e., surface of the material [micron depth] affected more than the material core). Typically, PP components are designed to be relatively thick (e.g., >1–2 mm) so as to withstand radiation processing. Sampling for GPC was random but mainly originated at the surface, thereby supporting these observations. The low reproducibility observed was assumed not to be associated with irradiation conditions but rather to result from intrinsic method variability. Although a widespread decrease of Mw with

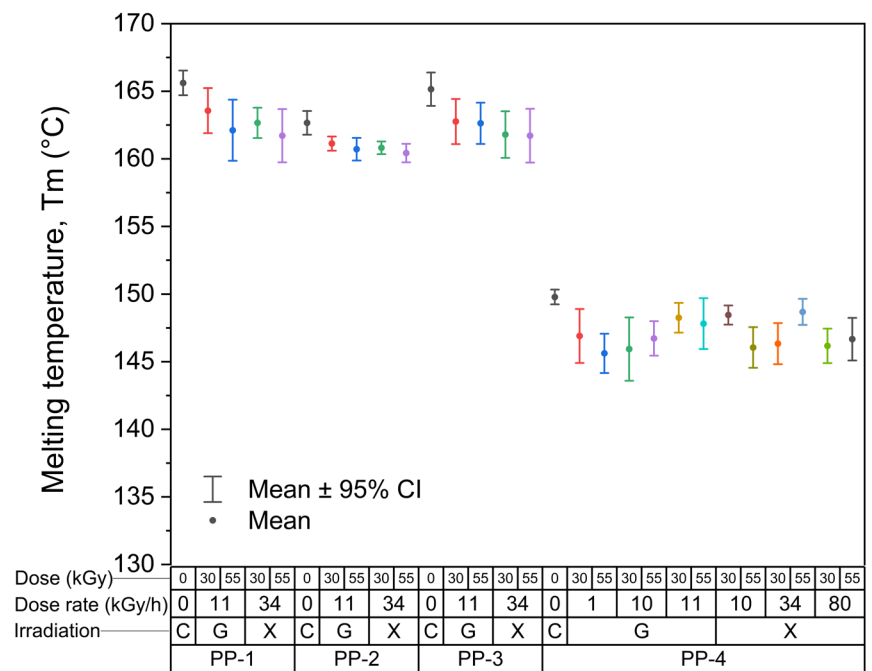


Figure 4. Melting temperature (T_m) measured for each polypropylene (PP) sample for each processing condition. Abbreviations used: C, control; G, gamma; X, X-ray.

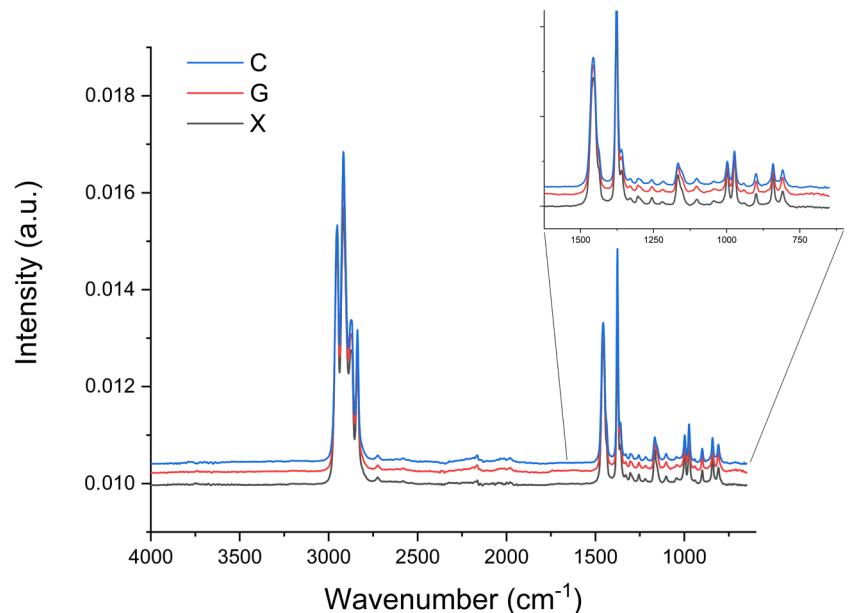


Figure 5. Attenuated total reflectance Fourier transform infrared spectroscopy spectra for polypropylene (PP)-4 material irradiated at 30 kGy. Abbreviations used: C, control; G, gamma; X, X-ray.

PP grades occurred, there was no notable degradation present globally in the other investigated properties between the two radiation sources and their parameters from the molecular weight measurements.

Conclusion

A multitechnique approach was used to investigate the effect of gamma and X-ray

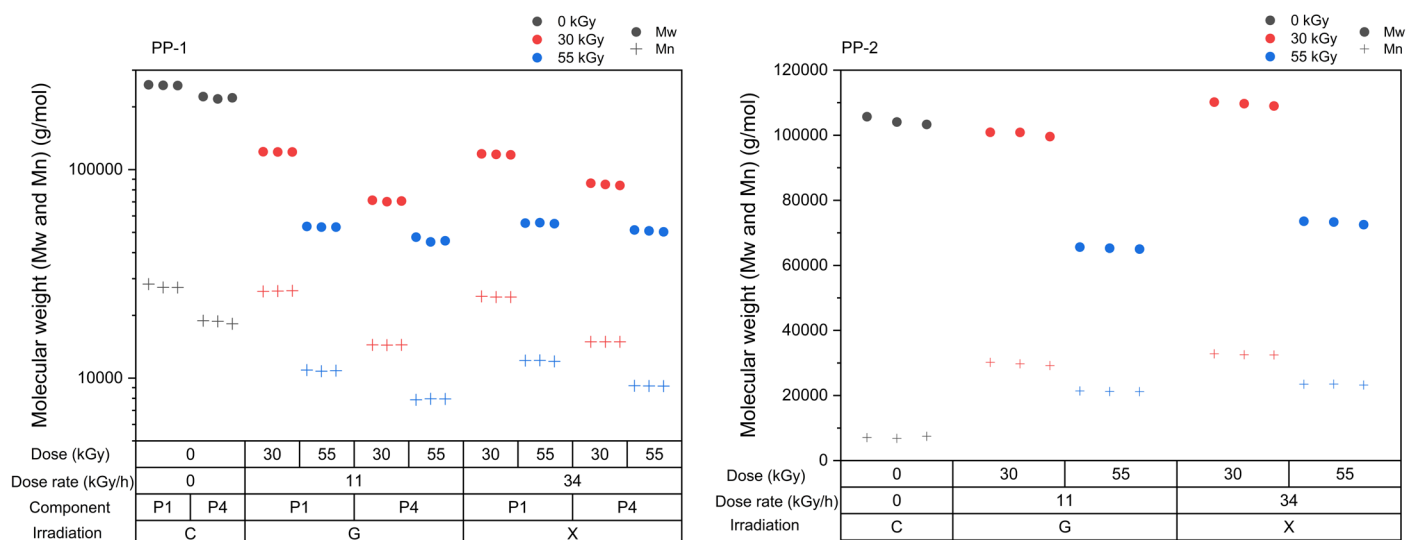


Figure 6. Weight average molecular weight (Mw) and number average molecular weight (Mn) for polypropylene (PP)-1 (left) and PP-2 (right). P1 and P4 are PP-1 components. Three replicates are plotted. Abbreviations used: C, control; G, gamma; X, X-ray.

irradiation on strategic materials currently used in the biopharmaceutical and medical device industry. Statistically significant results were observed, showing that the investigated thermal and chemical fingerprint properties were not altered within industrial sterilization conditions. This observation included T_m and the chemical fingerprints for all materials (HDPE, LDPE, and PP) assessed within the investigated experimental conditions bracketing routine industrial radiation processing (Table 5).

The molecular weight investigation revealed that HDPE and LDPE polymers have a tendency to cross-link and that chain scission largely occurred on PP polymers upon irradiation, irrespective of radiation technology and dose rate. These observations should be considered according to the polymer grades assessed. The irradiation

technologies (gamma and X-ray) and examined dose rate range (1–80 kGy/h) have equivalent influences within methodology uncertainties on modifications. The influences were confirmed at all doses delivered for both irradiation technologies. Of important note, all material grades studied in this work are currently in use and have been proven to be successfully irradiated using gamma. It is assumed that any modification from radiation processing either is occurring to a small extent or is limited to the material surface and, as a result, not affecting the current intended use.

This study also provided guidance for assessing material compatibility with new radiation technologies, while avoiding the need for a full investigatory process for each material. A study objective was to conclude on equivalency of multiple material groups

DSC	ATR-FTIR	GPC
Thermal properties (T_m)	Chemical fingerprints	Molecular weight (Mw and Mn)
HDPE*	HDPE†	HDPE‡
LDPE*	LDPE†	LDPE‡
PP*	PP†	PP‡

Table 5. Summary of analysis performed, properties targeted, material families and statistical assessment. The equivalency status comparing gamma and X-ray impact is also presented. *Equivalent from material science viewpoint and statistical evaluation. †Equivalent from material science viewpoint and PCA evaluation. ‡Equivalent from material science viewpoint; no statistical evaluation possible. Abbreviations used: ATR-FTIR; attenuated total reflectance Fourier transform infrared spectroscopy; DSC, differential scanning calorimetry; HDPE, high-density polyethylene; GPC, gel permeation chromatography; LDPE, low-density polyethylene; PP, polypropylene; T_m , melting temperature.

by using statistical hypotheses tests, such as the TOST method.¹⁹ An equivalence test assesses the scale of potential variance from an experimental perspective, which helps lead to an equivalence determination. Statistical hypothesis testing is a deterministic method that provides a rigorous and objective technique to draw conclusions from data sets. This approach can identify truly significant differences in results while differentiating from noise.⁶

The equivalency criteria for thermal properties and fingerprint evaluation used in the current work embrace the inherent variations found with these methods. As the molecular weight determination expressed intrinsic uncertainty in relation to the results, equivalency criteria of a change in Mn of less than 30% and a change in Mw of less than 25% are tentatively proposed. This should be confirmed by conducting supplementary (round-robin) testing.

In summary, based on the material test methods, radiation process parameters, and statistical methods described here, gamma and X-ray processing resulted in equivalent outcomes on the tested polymeric materials.

Acknowledgments

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