

The RecyClass PO Films Technical Committee conducted an extensive test campaign to assess the effect of electron-beam (EB) treatment on polyethylene (PE) films, with a specific focus on LLDPE and HDPE-rich MDOPE structures. The objective was to determine how EB treatment influences recyclability-relevant parameters such as Melt Flow Index (MFI), extrusion behaviour, or mechanical properties, and to define thresholds to be used within RecyClass Design for Recycling Guidelines. The test campaign was performed over 2024–2025 and included films produced from commercial polyethylene grades containing antioxidants, provided by Dow and Borealis. Energy Sciences, Incorporated (ESI) supported the test campaign, in particular by treating the films with their machines, according to specific conditions within a specific range of radiation dose and voltage. The results showed clear correlations between the average received dose (\bar{d}) and changes in recyclability-critical parameters. The RecyClass PO Films TC concluded that electron-beam irradiation must remain a surface treatment, and compatibility thresholds were established according to \bar{d} .

The experimental plan consisted of two consecutive steps. In the first step, the PO Films TC investigated LLDPE films treated at different doses and voltages. The correlation between the nominal irradiation conditions and the average received dose (\bar{d}) was established using electron depth-dose profiles (see Annex I). In the second step, the test matrix was expanded to include MDOPE films with higher HDPE content, in order to verify the model and evaluate material-dependent effects. Across both materials, a wide range of nominal EB conditions was applied (see Annex II). The correlation with \bar{d} enabled a unified comparison of results across thicknesses, voltages, and doses.

Film samples were produced from the following materials:

- LLDPE (100 μm): LLDPE Dowlex 2045G (density 0.920 g/cm^3 ; MFI 1 $\text{g}/10$ min at 190°C/2.16 kg).
- MDOPE (120 μm): Trilayer made of BorShape FX1003 (density 0.941 g/cm^3 ; MFI 0.35 $\text{g}/10$ min) and Borstar FB5560 (density 0.956 g/cm^3 ; MFI 0.8 $\text{g}/10$ min).

All samples contained antioxidants. No dilutions were performed prior to extrusion to ensure consistent assessment of the effect of EB treatment. The melt pressure was monitored during the reprocessing step, and MFI was measured on the produced pellets. Obtained pellets were then blended with 50% of virgin LDPE to produce 25 μm films for gels and mechanical characterisations.

Across LLDPE and MDOPE samples, the average dose \bar{d} proved to be the determining factor influencing all measured properties. The tests confirmed that increases in \bar{d} lead to significant increase of melt pressure during extrusion, higher gel formation, decreasing MFI, and clear deterioration of mechanical performance.

In LLDPE films, low \bar{d} values (< 5 kGy) showed results remaining within RecyClass benchmark recommendations despite an increase of the melt pressure during pelletisation. At moderate \bar{d} values (between 5–9 kGy) modest increases in gel count could be observed but MFI, tear strength and melt pressure started to be out of the benchmark recommendations. With \bar{d} values above 13 kGy a steep rise in gel formation up to several hundreds of defects per film were identified. These changes directly affected extrusion stability and resulted in significant loss of mechanical performance, such as reduced dart impact resistance and decreased elongation at break. In parallel, MDOPE films exhibited a similar trend, although the extent of the mechanical property degradation differed due to their higher intrinsic density and semi-crystalline behaviour. This could be well observed with a less intense impact on the evolution of the MFI (out of benchmark at \bar{d} > 13 kGy) and number of gels (out of benchmark at \bar{d} > 19 kGy) with the intensity of the EB treatment for samples produced from MDOPE films. Mechanical tests on 25 μ m diluted films further revealed consistent reductions in tear resistance, tensile strength, and elongation at break performance when \bar{d} exceeded 15 kGy.

Overall, the fitting model developed during the first stage was validated for HDPE-rich MDOPE, confirming the applicability of \bar{d} as a reliable, material-agnostic indicator. The results consistently demonstrated that electron-beam treatment becomes detrimental to recyclability once \bar{d} surpasses specific thresholds, due to excessive crosslinking and gel formation that directly affect the viscosity and mechanical performances of the recycled material.

Based on the results obtained during the test campaign, the RecyClass PO Films TC established compatibility thresholds for EB-treated PE films. These thresholds classify the impact of EB-treatment on recyclability according to the average received dose (\bar{d}), regardless of the nominal irradiation settings and the nature of the PE grade. Note that the fact that the tests were done without dilution of the treated films, was also taken into account in the PO Films TC decision.

Therefore, the following Design for Recycling recommendations for PE films were delivered:

- **Full compatibility:** EB treated films with $\bar{d} < 9$ kGy.

In general, these conditions preserve the generation of gels, as well as the mechanical performance within benchmark ranges.

- **Limited compatibility:** EB treated films with $9 \text{ kGy} \leq \bar{d} < 15 \text{ kGy}$.

In this range, MFI and gels display deviations, and some mechanical performances start to deviate from a non-treated PE film.

- **Non compatibility:** EB treated films with $\bar{d} \geq 15$ kGy.

These treatments lead to excessive crosslinking and gel formation that render the material unsuitable for mechanical recycling in the PE stream.

The results confirm that electron-beam treatment should only be applied as a surface treatment in PE-based packaging structures intended for recycling. Processes that induce deep crosslinking must be avoided unless validated with dedicated recyclability testing.

Standardised methodologies for \bar{d} -measurement and simplified industry guidelines can be found in the Annexes I and III, aiming to support packaging designers and converters in implementing EB processes that remain fully compatible with high-quality mechanical recycling. Note that, in the case of a lamination, the treated film should be considered separated, and a dilution factor should then be applied to the \bar{d} value, while films that would go through multiple passes must use a multiplication factor to obtain the accurate \bar{d} value.

About RecyClass

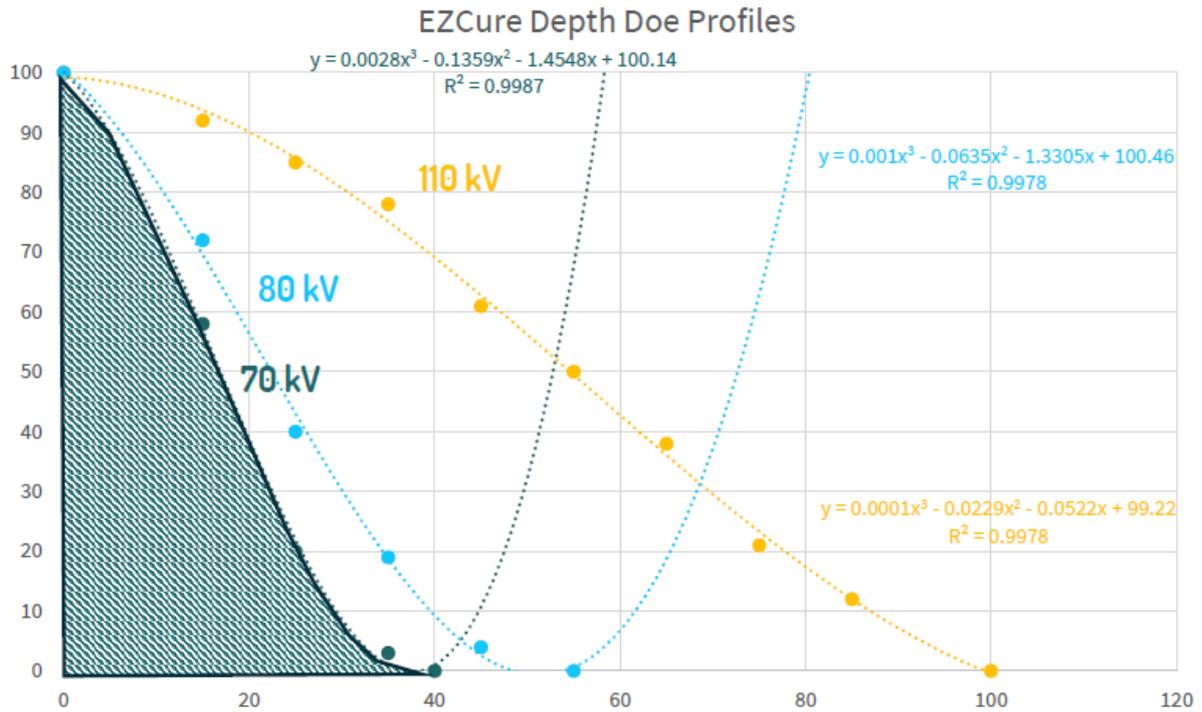
RecyClass is a non-profit, cross-industry initiative advancing recyclability, bringing transparency to the origin of plastic waste and establishing a harmonized approach toward recycled plastic calculation & traceability in Europe. RecyClass develops Recyclability Evaluation Protocols and scientific testing methods for innovative plastic packaging materials which serve as the base for the Design for Recycling Guidelines and the RecyClass Online Tool. RecyClass established Recyclability Certifications for plastic packaging, Recycling Process Certification and Recycled Plastics Traceability Certification for plastic products.

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Annex I



$$\bar{d} = \text{Area under curve} / t * \text{EBD}$$

With
 Area under curve ($\mu\text{m} * (\%)$)
 t : thickness of the film (μm)
 EBD : EB irradiation dose (kGy)

Here : $\bar{d} = 1707 / 100 * 50 * 0.01 = 8.5 \text{ kGy}$

Figure 1. Determination of the average received dose (\bar{d}) based on depth-dose profiles

Annex II

Table 1. Treatment conditions of the LLDPE and MDOPE-based samples

| STEP 1 - 2024 | Test # | composition | e-beam dose (kGy) | voltage (kV) | Thickness (μm) | đ (kGy) |
|---------------|--------|------------------------------|-------------------|--------------|----------------|---------|
| | 0 | LLDPE <u>Dowlex</u> 2045G | Non treated | | 100 | 0 |
| | 1 | LLDPE <u>Dowlex</u> 2045G | 30 | 70 | 100 | 5.20 |
| | 2 | LLDPE <u>Dowlex</u> 2045G | 50 | 70 | 100 | 8.67 |
| | 4 | LLDPE <u>Dowlex</u> 2045G | 100 | 70 | 100 | 17.35 |
| | 8 | LLDPE <u>Dowlex</u> 2045G | 75 | 80 | 100 | 17.09 |
| STEP 2 - 2025 | Test # | composition | e-beam dose (kGy) | voltage (kV) | Thickness (μm) | đ (kGy) |
| | MDO1 | MDOPE <u>BorShape</u> FX1003 | Non treated | | 120 | 0 |
| | MDO2 | MDOPE <u>BorShape</u> FX1003 | 50 | 70 | 120 | 7.23 |
| | MDO3 | MDOPE <u>BorShape</u> FX1003 | 80 | 70 | 120 | 11.56 |
| | MDO4 | MDOPE <u>BorShape</u> FX1003 | 80 | 80 | 120 | 15.19 |
| | MDO5 | MDOPE <u>BorShape</u> FX1003 | 100 | 80 | 120 | 18.99 |
| | LLDPE1 | LLDPE <u>Dowlex</u> 2045G | 90 | 70 | 100 | 15.61 |
| | LLDPE2 | LLDPE <u>Dowlex</u> 2045G | 75 | 70 | 100 | 13 |
| | LLDPE3 | LLDPE <u>Dowlex</u> 2045G | 50 | 80 | 100 | 11.39 |

Annex III

Table 2. Simplified guidances for calculation of the average received dose (d)

| @ 70 kV | | Thickness (µm) | | | | | | | | |
|-----------|-----|----------------|------|------|------|------|------|-----|-----|-----|
| | | 20 | 40 | 60 | 80 | 100 | 200 | 300 | 400 | 500 |
| EBD (kGy) | 30 | 21.9 | 12.8 | 8.5 | 6.4 | 5.1 | 2.6 | 1.7 | 1.3 | 1.0 |
| | 50 | 36.5 | 21.3 | 14.2 | 10.7 | 8.5 | 4.3 | 2.8 | 2.1 | 1.7 |
| | 70 | 51.1 | 29.9 | 19.9 | 14.9 | 11.9 | 6.0 | 4.0 | 3.0 | 2.4 |
| | 80 | 58.4 | 34.1 | 22.8 | 17.1 | 13.7 | 6.8 | 4.6 | 3.4 | 2.7 |
| | 90 | 65.7 | 38.4 | 25.6 | 19.2 | 15.4 | 7.7 | 5.1 | 3.8 | 3.1 |
| | 100 | 73.0 | 42.7 | 28.4 | 21.3 | 17.1 | 8.5 | 5.7 | 4.3 | 3.4 |
| | 120 | 87.6 | 51.2 | 34.1 | 25.6 | 20.5 | 10.2 | 6.8 | 5.1 | 4.1 |
| | 150 | 109.5 | 64.0 | 42.7 | 32.0 | 25.6 | 12.8 | 8.5 | 6.4 | 5.1 |

| @ 80 kV | | Thickness (µm) | | | | | | | | |
|-----------|-----|----------------|------|------|------|------|------|------|-----|-----|
| | | 20 | 40 | 60 | 80 | 100 | 200 | 300 | 400 | 500 |
| EBD (kGy) | 30 | 24.2 | 16.8 | 11.3 | 8.5 | 6.8 | 3.4 | 2.3 | 1.7 | 1.4 |
| | 50 | 40.3 | 27.9 | 18.9 | 14.2 | 11.3 | 5.7 | 3.8 | 2.8 | 2.3 |
| | 70 | 56.5 | 39.1 | 26.5 | 19.8 | 15.9 | 7.9 | 5.3 | 4.0 | 3.2 |
| | 80 | 64.5 | 44.7 | 30.2 | 22.7 | 18.1 | 9.1 | 6.0 | 4.5 | 3.6 |
| | 90 | 72.6 | 50.3 | 34.0 | 25.5 | 20.4 | 10.2 | 6.8 | 5.1 | 4.1 |
| | 100 | 80.7 | 55.9 | 37.8 | 28.3 | 22.7 | 11.3 | 7.6 | 5.7 | 4.5 |
| | 120 | 96.8 | 67.1 | 45.3 | 34.0 | 27.2 | 13.6 | 9.1 | 6.8 | 5.4 |
| | 150 | 121.0 | 83.8 | 56.7 | 42.5 | 34.0 | 17.0 | 11.3 | 8.5 | 6.8 |

| @ 90 kV | | Thickness (µm) | | | | | | | | |
|-----------|-----|----------------|-------|------|------|------|------|------|------|-----|
| | | 20 | 40 | 60 | 80 | 100 | 200 | 300 | 400 | 500 |
| EBD (kGy) | 30 | 26.3 | 20.5 | 15.0 | 11.2 | 9.0 | 4.5 | 3.0 | 2.2 | 1.8 |
| | 50 | 43.8 | 34.2 | 24.9 | 18.7 | 15.0 | 7.5 | 5.0 | 3.7 | 3.0 |
| | 70 | 61.3 | 47.9 | 34.9 | 26.2 | 21.0 | 10.5 | 7.0 | 5.2 | 4.2 |
| | 80 | 70.0 | 54.8 | 39.9 | 30.0 | 24.0 | 12.0 | 8.0 | 6.0 | 4.8 |
| | 90 | 78.8 | 61.6 | 44.9 | 33.7 | 27.0 | 13.5 | 9.0 | 6.7 | 5.4 |
| | 100 | 87.5 | 68.4 | 49.9 | 37.5 | 30.0 | 15.0 | 10.0 | 7.5 | 6.0 |
| | 120 | 105.1 | 82.1 | 59.9 | 44.9 | 36.0 | 18.0 | 12.0 | 9.0 | 7.2 |
| | 150 | 131.3 | 102.7 | 74.8 | 56.2 | 44.9 | 22.5 | 15.0 | 11.2 | 9.0 |

| @ 110 kV | | Thickness (µm) | | | | | | | | |
|-----------|-----|----------------|-------|-------|------|------|------|------|------|------|
| | | 20 | 40 | 60 | 80 | 100 | 200 | 300 | 400 | 500 |
| EBD (kGy) | 30 | 28.8 | 26.4 | 23.2 | 19.6 | 16.1 | 8.1 | 5.4 | 4.0 | 3.2 |
| | 50 | 48.0 | 44.1 | 38.7 | 32.7 | 26.9 | 13.5 | 9.0 | 6.7 | 5.4 |
| | 70 | 67.1 | 61.7 | 54.2 | 45.8 | 37.7 | 18.8 | 12.6 | 9.4 | 7.5 |
| | 80 | 76.7 | 70.5 | 61.9 | 52.4 | 43.1 | 21.5 | 14.4 | 10.8 | 8.6 |
| | 90 | 86.3 | 79.3 | 69.7 | 58.9 | 48.4 | 24.2 | 16.1 | 12.1 | 9.7 |
| | 100 | 95.9 | 88.1 | 77.4 | 65.5 | 53.8 | 26.9 | 17.9 | 13.5 | 10.8 |
| | 120 | 115.1 | 105.7 | 92.9 | 78.5 | 64.6 | 32.3 | 21.5 | 16.1 | 12.9 |
| | 150 | 143.9 | 132.2 | 116.1 | 98.2 | 80.7 | 40.4 | 26.9 | 20.2 | 16.1 |

| @ 200 kV | | Thickness (µm) | | | | | | | | |
|-----------|-----|----------------|-------|-------|-------|-------|-------|------|------|------|
| | | 20 | 40 | 60 | 80 | 100 | 200 | 300 | 400 | 500 |
| EBD (kGy) | 30 | 29.9 | 30.1 | 30.0 | 29.8 | 29.5 | 25.7 | 19.9 | 14.2 | 11.4 |
| | 50 | 49.8 | 50.1 | 50.1 | 49.7 | 49.1 | 42.8 | 33.1 | 23.7 | 19.0 |
| | 70 | 69.7 | 70.1 | 70.1 | 69.6 | 68.8 | 59.9 | 46.3 | 33.2 | 26.5 |
| | 80 | 79.7 | 80.2 | 80.1 | 79.6 | 78.6 | 68.4 | 52.9 | 37.9 | 30.3 |
| | 90 | 89.6 | 90.2 | 90.1 | 89.5 | 88.4 | 77.0 | 59.6 | 42.7 | 34.1 |
| | 100 | 99.6 | 100.2 | 100.1 | 99.5 | 98.3 | 85.6 | 66.2 | 47.4 | 37.9 |
| | 120 | 119.5 | 120.2 | 120.2 | 119.4 | 117.9 | 102.7 | 79.4 | 56.9 | 45.5 |
| | 150 | 149.4 | 150.3 | 150.2 | 149.2 | 147.4 | 128.3 | 99.3 | 71.1 | 56.9 |