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Too many structures for the same function: Market evidence of circularity barriers in food packaging

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ABSTRACT

The transition towards circular food packaging requires not only regulatory compliance but also material and structural harmonization. This study analyzes 163 multilayer films from commercial food packaging available on the European market to quantify structural diversity and assess implications for recyclability. Forty-two distinct multilayer configurations and twenty-seven polymer combinations were identified, with no systematic relationship to food category, film thickness, or functional requirements. Functionally similar packages frequently relied on materially incompatible or over-engineered polymer combinations, revealing a fragmented and non-standardized packaging landscape.

Although all analyzed structures comply with current European food-contact regulations (EC 1935/2004 and EU 10/2011), their diversity and incompatibility hinder mechanical and chemical recycling, challenging the objectives of the forthcoming Packaging and Packaging Waste Regulation (PPWR). Overall, the results provide quantitative, market-level evidence of structural redundancy and demonstrate how fragmented design practices undermine design-for-recycling principles and the implementation of circular economy strategies in food packaging.

1. Introduction

The transition to a circular economy for plastics, as outlined in the European Green Deal and the Circular Economy Action Plan, requires the integration of sustainability criteria into packaging design, adding a new layer of complexity to traditional performance-driven requirements, while ensuring that the primary function of packaging-food protection, shelf life, and safety-is not compromised. (Liu et al., 2023). Although multilayer flexible packaging films represent a relatively small mass fraction of lightweight packaging waste streams, they pose a disproportionate challenge for recycling systems due to their structural complexity and material heterogeneity (Fig. 1) (Callewaert et al., 2023; Shittu et al., 2021; Thomassen et al., 2022). Typically, these multilayer films consist of combinations of layers of polyethylene (PE), polypropylene (PP), polyamide (PA), polyethylene terephthalate (PET), ethylene vinyl alcohol (EVOH), and tie resins (Marsh and Bugusu, 2007; Vegter et al., 2020). While such complexity ensures product safety and performance and reflects the need to balance multiple design

objectives-including material efficiency, shelf-life, and cost-it often leads to structurally diverse and materially incompatible systems that challenge recycling processes. In addition, the presence of inks, coatings, and varnishes, commonly based on nitrocellulose resins, introduces further constraints related to food-contact safety during reprocessing, as recently reported (Canellas et al., 2017; Guo et al., 2024; Lisiecki et al., 2024; Prielinger et al., 2025). Importantly, this complexity is also linked to broader policy and market drivers, as multilayer flexible packaging has been widely adopted due to its ability to reduce material use and improve product preservation, even if this comes at the expense of recyclability. Together, these factors complicate alignment with design-for-recycling principles promoted in the proposed Packaging and Packaging Waste Regulation (PPWR) (Ellen Macarthur Foundation; World Economic Forum; McKinsey&Co, 2016; Versino et al., 2023; Walker et al., 2020).

Despite growing legislative pressure, empirical evidence quantifying the degree of structural fragmentation in the food-packaging market remains scarce. Available studies suggest that packaging design is

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largely driven by functional and commercial considerations, often resulting in proprietary multilayer combinations whose end-of-life compatibility is not systematically addressed, leading to structural redundancies that compromise both recyclability and traceability (Soares et al., 2022). In this context, all films in this study were analyzed using complementary spectroscopic, thermal, and microscopic techniques (FTIR, DSC, TGA, and SEM) to identify their polymer composition and layer structure. The purpose of these analyses was not to assess barrier or mechanical performance, but to document the extent of material and structural diversity currently used for functionally similar food applications. This market-level analytical mapping provides an evidence-based framework to discuss how structural redundancy and material incompatibility act as systemic barriers to circular packaging.

In this work, 163 commercial food-packaging films were collected from different supermarkets in Spain from commercially available products, and systematically analyzed to quantify the extent of structural and compositional diversity in the current market, assess functional redundancy across product categories, and discuss the implications of this fragmentation for circularity and compliance with forthcoming European packaging regulations, including the proposed PPWR (Collins et al., 2021; European Commission, 2004; Nishimura, 2018).

2. Materials and methods

2.1. Materials

All materials used in this study were commercially available. Solvents for layer separation included dimethylsulfoxide (DMSO, VWR Chemicals, 99.9%), toluene (Sigma-Aldrich, $\geq 99.5\%$), formic acid (Sigma-Aldrich, $\geq 98\%$), hydrochloric acid (HCl, Sigma-Aldrich, 37%), and hexane (Fisher Chemical, $\geq 95\%$).

A total of 103 multilayer food packages (163 films: 104 top films and 59 base trays) were analyzed. Packaging samples were collected from the European retail market (Spain), over the period 2024–2025, covering a broad range of food categories (e.g., meat, dairy, snacks, ready-to-eat products). The films were obtained directly from commercially available products, rather than from post-consumer waste streams or directly from manufacturers, in order to reflect real market conditions. The selection aimed to capture structural diversity across commonly used packaging solutions rather than to provide a statistically representative sampling of all packaging types. The packaging samples

identification and characterization are included in the Supplementary Information (SI), section S6. Films were separated into top and base components, washed with soap and water, followed by a rinse with hexane to remove any food residues or surface contaminants, and labeled individually. Detailed information about the composition of the samples, along with their associated food categories and structural classification, is provided in Tables S1 and S2 in SI, Section S1.

2.2. Methods and instrumentation

Film thickness was measured with a micrometer, averaging five readings from different points on each sample.

Infrared spectra (FTIR) of both the outer and inner layers of each film (of both top films and base trays) were recorded after drying the samples at 60 °C for two hours. Measurements were performed using a Jasco FT/IR-4200 spectrometer equipped with an ATR-PRO410-S accessory.

Thermal properties were evaluated by TGA and DSC. TGA was performed under nitrogen and air atmospheres with a TGA Q50 analyzer (TA Instruments) (~5 mg samples, heating rate of 10 °C/min up to 800 °C). DSC analyses were conducted on a Q200 instrument (TA Instruments) under nitrogen (50 mL/min), using ~15 mg samples. A heat-cool-heat cycle from -80 °C to 300 °C at 20 °C/min was used.

Mechanical tests were performed on a Shimadzu EZ Test machine (5 × 50 mm, 5 mm/min, 9.44 mm gauge). For each film type, at least five samples were tested, and the results were averaged after excluding the highest and lowest values to improve data reliability.

A scanning electron microscope (SEM) (JEOL JSM-6460LV) was used to examine layer structure after cryo-fracture in liquid N₂ and gold coating. The thickness of individual layers was determined by image analysis from multiple micrographs obtained for each film at different magnifications, using the scale bar as reference. When necessary, high-magnification images were employed to improve layer boundary definition. For each sample, mean layer thickness values were calculated from at least three measurements taken at different regions of the same film cross-section. Adhesive or tie layers, when present, were not included in the reported thickness values, as their boundaries were often indistinct or below the resolution limit of the micrographs.

When the composition and layering sequence of the films could not be fully determined by SEM, DSC, and FTIR analyses of the intact upper and lower layers, a solvent-based separation method was employed. Strips (~0.5–1 cm × 3 cm) were immersed in 1 cm of hot solvent: DMSO (100 °C, 30 min) for polyurethane adhesives; DMSO:H₂O (60:40, 95 °C,

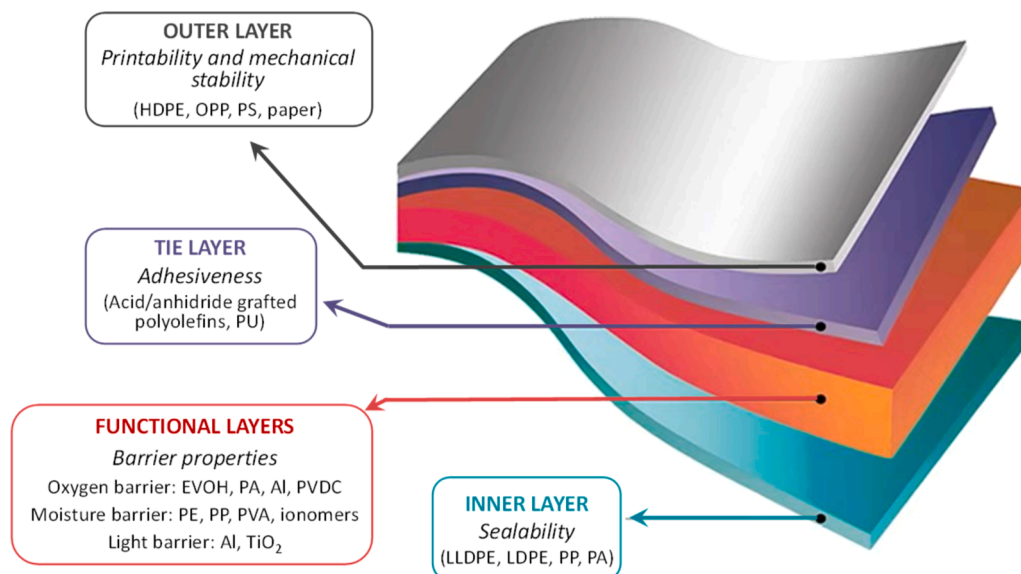


Fig. 1. Scheme and description of polymer based multilayer packaging technology (Anukiruthika et al., 2020).

30 min) for EVOH; toluene (100°C, 30 min) for PE and PP; formic acid (100°C, 30 min) for PA; HCl (heated to ~70°C, 15 min) for aluminum. Residual layers were analyzed by FTIR.

To complement the literature-based barrier analysis, the oxygen transmission rate (OTR) was experimentally determined only for a subset of five commercial films intended for the same application (processed-meat packaging), randomly selected from the analyzed samples. These measurements were not performed for the full set of films included in the study, but rather as a targeted experimental verification to compare, under a single testing protocol, the barrier variability observed in the literature. OTR was determined according to ASTM F1927-20 using a MOCON OXTRAN 2/22 instrument. Tests were carried out at 23°C and 85% relative humidity after >2 h of instrument pre-conditioning. The test specimens had a nominal exposed area of 50 cm². The oxygen partial pressure was 1 atm and the carrier-gas flow was set at 10 cm³ min⁻¹. Results are reported as OTR normalised to area and pressure, in cm³ m⁻² 24 h⁻¹ atm⁻¹ at 23°C/85% RH. Measurements were performed at least in triplicate, using specimens taken from the same package.

3. Results and discussion

A total of 163 multilayer films from commercial food packaging were analyzed. In 104 of these cases, the film functioned as a top sealing layer (or was part of a fully sealed flexible package with no rigid base), while

59 samples served as rigid or semi-rigid base trays. This distinction is essential, as lids and base trays have different structural and functional roles within packaging systems. The samples were categorized into 18 food groups to explore possible correlations between packaging design and product type (1. chilled prepared food, 2. fresh plant-based meat alternatives, 3. cheese, 4. cured meat, 5. sliced cooked meat, 6. chilled prepared vegan food, 7. chilled fresh meat, 8. chilled convenience food, 9. cooked sausages, 10. savoury snack, 11. frozen vegetables, 12. frozen convenience food, 13. frozen partially cooked food, 14. dried fruit, 15. coffee, 16. cereals, 17. sweet snack, 18. pet food). The composition of the multilayer films, their layout and thickness of each layer and the type of food they contained are described in the Supplementary Information (SI), section S1, Tables S1 and S2.

3.1. Structural diversity between tops and bases

The functional requirements of lid films and base trays differ considerably: lids are typically designed to provide barrier properties (against oxygen, moisture or aroma), sealability, and visibility; whereas trays, in addition to barrier requirements, provide structural strength, impact resistance, and heat resistance for microwave use.

This distinction is reflected in their physical properties. The average thickness (Tables S1, S2 and S3 in SI, Section S1) of base trays was 0.287 mm (range: 0.079–0.803 mm). While lid films were much thinner, averaging 0.073 mm (range: 0.023–0.133 mm), with one outlier (sample

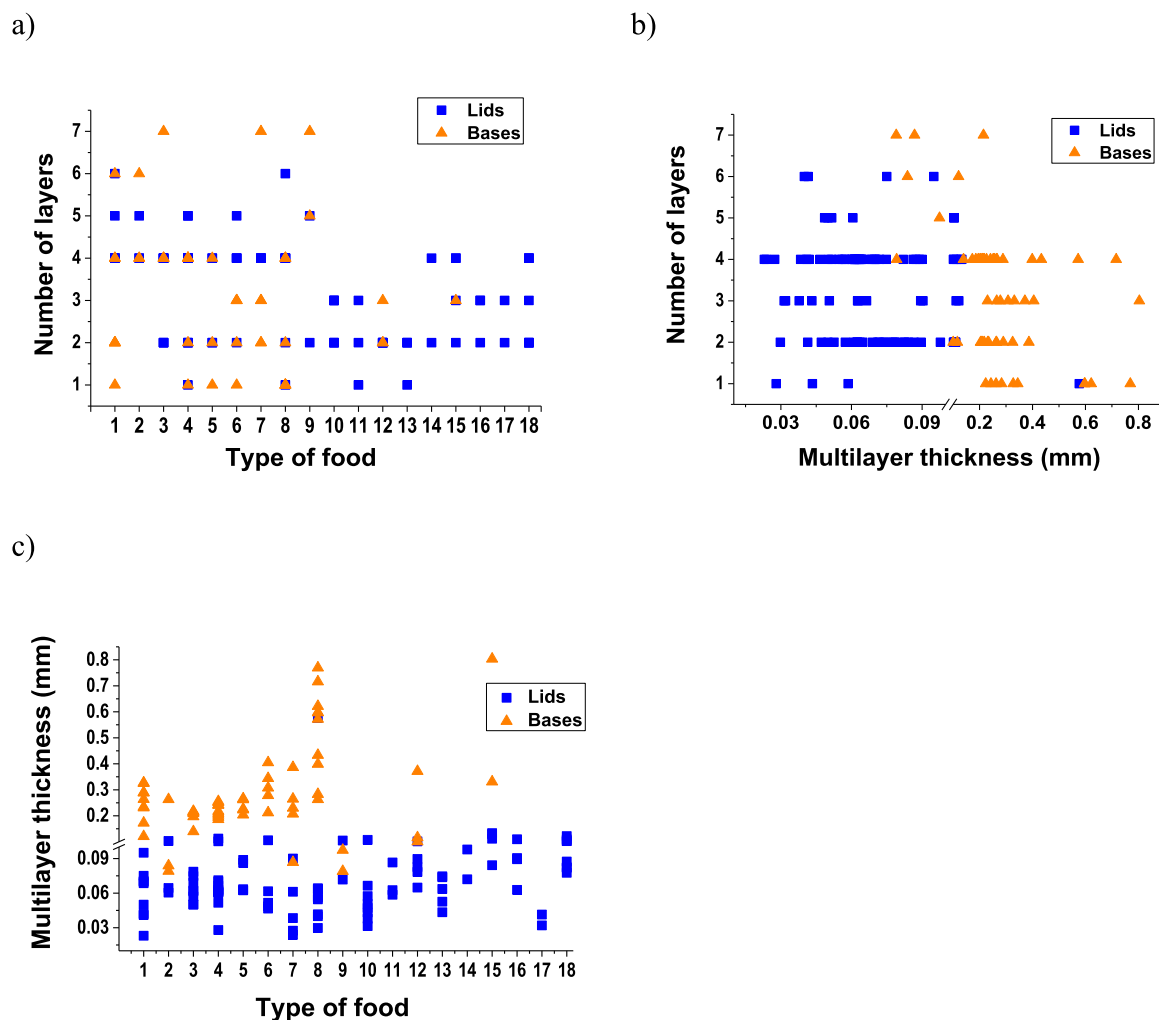


Fig. 2. Relationships between the number of layers, the type of food and the multilayer film's thickness. a) Number of layers in lids and bases across 18 food types, b) relationship between multilayer thickness and number of layers in lids and bases, and c) multilayer thickness of lids and bases across 18 food types.

48, 0.576 mm) designed for structural support. These values align with their respective functional demands.

When comparing packaging to food type, general trends were observed (Fig. 2c, and Tables S1 and S2, SI, Section S1). Heavier or products with high mechanical demands on packaging (e.g., requiring puncture resistance or structural integrity), such as fresh meat, ready meals, or semi-solid preparations, tended to be packaged with thicker base trays, regardless of the base tray composition. In contrast, lightweight or low-moisture items such as sliced cheese or snacks often use thinner structures. However, even within the same food category, substantial variation in thickness was observed. Overall, film thickness appears to be influenced by a combination of mechanical requirements and packaging format, rather than food type alone. This suggests that while mechanical requirements contribute to design decisions, packaging configurations are also shaped by additional factors such as supplier choice, cost, and marketing strategies. Importantly, these decisions are often influenced by risk acceptance criteria defined by brand owners, leading to different design choices for similar products. Furthermore, variations in targeted shelf-life may result in different barrier requirements (e.g., OTR, CO₂ transmission rate, and WVTR), reinforcing the lack of a direct, one-to-one relationship between food type and packaging structure.

Despite thickness differences, both lids and bases showed comparable stiffness (Tables S4, S5 and S6, Section S2). The average Young's modulus across the sample set was approximately 700 MPa for both lids and base trays, indicating that stiffness is primarily achieved through material selection and multilayer structure rather than by increasing thickness. Lid films exhibited higher tensile strength (62 MPa vs. 48 MPa), likely due to the use of oriented or co-extruded high-barrier layers that also enhance sealing performance.

Thermogravimetric analysis (Tables S7, S8 and S9 SI, Section 3) showed slightly higher onset and T_{10} degradation temperatures in base trays under both nitrogen and air atmospheres. These differences, although subtle, suggest greater use of thermally stable materials like PET or PP or filler reinforcements, particularly relevant for heatable foods. Lid films, which often contain a higher proportion of ductile materials like PE for sealability, showed earlier degradation under the same conditions.

Nevertheless, attributing mechanical or thermal performance to specific structural features remains challenging, as the films exhibit high variability in layer thickness or proportions and composition, making direct comparisons across samples highly difficult.

3.2. Multilayer composition and variability

Beyond thickness, the structural complexity of multilayer films was further assessed by examining the number of functional layers and material diversity. Across the dataset, and without considering the thickness of each layer, 42 distinct multilayer configurations were identified when both polymer type and layer sequence were considered. Simplifying the analysis by grouping samples according to polymer types, regardless of order or number, resulted in 27 unique material combinations (Tables S1 and S2, SI, Section S1).

The number of functional layers (excluding adhesives) ranged from 1 to 7 (Fig. 2a, and Table S3 in the SI). It might be expected that lid films, given their barrier role and thinner profiles, would require more complex multilayer designs. However, data showed that base trays often contained as many, or even more, layers than lids. Several base tray samples had six or seven layers, despite already having high thicknesses (>0.7 mm). This may reflect over-engineering, cost-driven material substitution, or efforts to balance rigidity and barrier performance. Conversely, many lid films had just 3–4 layers, even in cases when good barrier properties were essential. This expectation is based on the fact that different polymers provide complementary barrier properties: polyolefins such as PE and PP offer good moisture resistance, while additional layers such as EVOH are typically required to ensure

sufficient oxygen barrier, particularly in applications such as modified-atmosphere packaging for fresh meat. This observation highlights that layer thickness and the number of layers are not directly correlated with functional performance, which instead depends on the selection and combination of polymers tailored to the specific barrier requirements of the product.

Plots comparing number of layers vs. food type and film thickness (Fig. 2a and b) revealed no clear pattern or rationalization. For example, categories like sliced meat, ready meals, or prepared foods (types 1, 4 or 8, respectively) used over five different multilayer structures each. In contrast, some structures, such as PET/EVOH/PE, appeared across unrelated food types (e.g., hard cheese and cooked meats), even though the shelf-life, moisture, and gas exchange characteristics of these products differ. This suggests that packaging design is not solely determined by technical requirements, but is also influenced by commercial, supply-chain, and company-specific factors, contributing to structural fragmentation and hindering standardization efforts toward recyclability.

The analysis of the frequency of the type of multilayer film usage in the samples confirms this inconsistency (Fig. 3 and Tables S10, S11, and S12 of in the SI, Section S4). Structures like PET/PE/EVOH, PET/PE, or PE alone were found in multiple food categories, suggesting that similar structural solutions are applied across different food categories, despite variations in product-specific requirements. Even food types with similar apparent barrier requirements (e.g., chilled prepared meals or cooked meat) used highly varied films. Likewise, frozen categories such as vegetables, convenience food, and partially cooked products also showed structural diversity, even though their barrier requirements are generally lower due to storage at subzero temperatures. However, this diversity cannot be fully explained by a limited set of parameters such as OTR or WVTR alone. In practice, different food products may require additional functionalities, including CO₂ retention, puncture resistance, or protection against light and UV radiation, depending on factors such as composition, packaging atmosphere, and storage conditions. For instance, modified-atmosphere packaging for fresh meat, certain dairy products, or seafood may impose specific CO₂ barrier requirements, while products with sharp edges or bones may require enhanced mechanical resistance. Furthermore, barrier performance can evolve over time (e.g., due to moisture-induced changes in EVOH), particularly in extended shelf-life applications.

Despite these functional differences, the extent of structural variability observed within similar food categories suggests that not all design choices are strictly determined by technical requirements alone. Factors such as targeted shelf-life, risk acceptance, and company-specific design strategies likely also contribute to the coexistence of multiple materially distinct solutions for comparable applications—further complicating efforts to harmonize recycling or material recovery strategies.

Overall, the observed packaging diversity indicates that equivalent structural performance is achieved through a wide range of materially distinct multilayer architectures, rather than through a limited set of standardized engineering solutions. The absence of clear correlations between film structure, thickness, and food application points to a highly fragmented design landscape. From a regulatory and circular-economy perspective, such fragmentation is problematic, as current and forthcoming EU policies aim to ensure not only food safety compliance but also recyclability at scale. However, achieving greater alignment in packaging design would likely require a clearer legal framework at the European level, as voluntary or market-driven approaches alone may be insufficient to drive structural harmonization.

3.3. Barrier performance

Beyond structural characterization, an important question is whether the wide variety of multilayer architectures identified in the market translates into meaningful functional differences. To address this, the barrier-performance analysis was carried out in two complementary

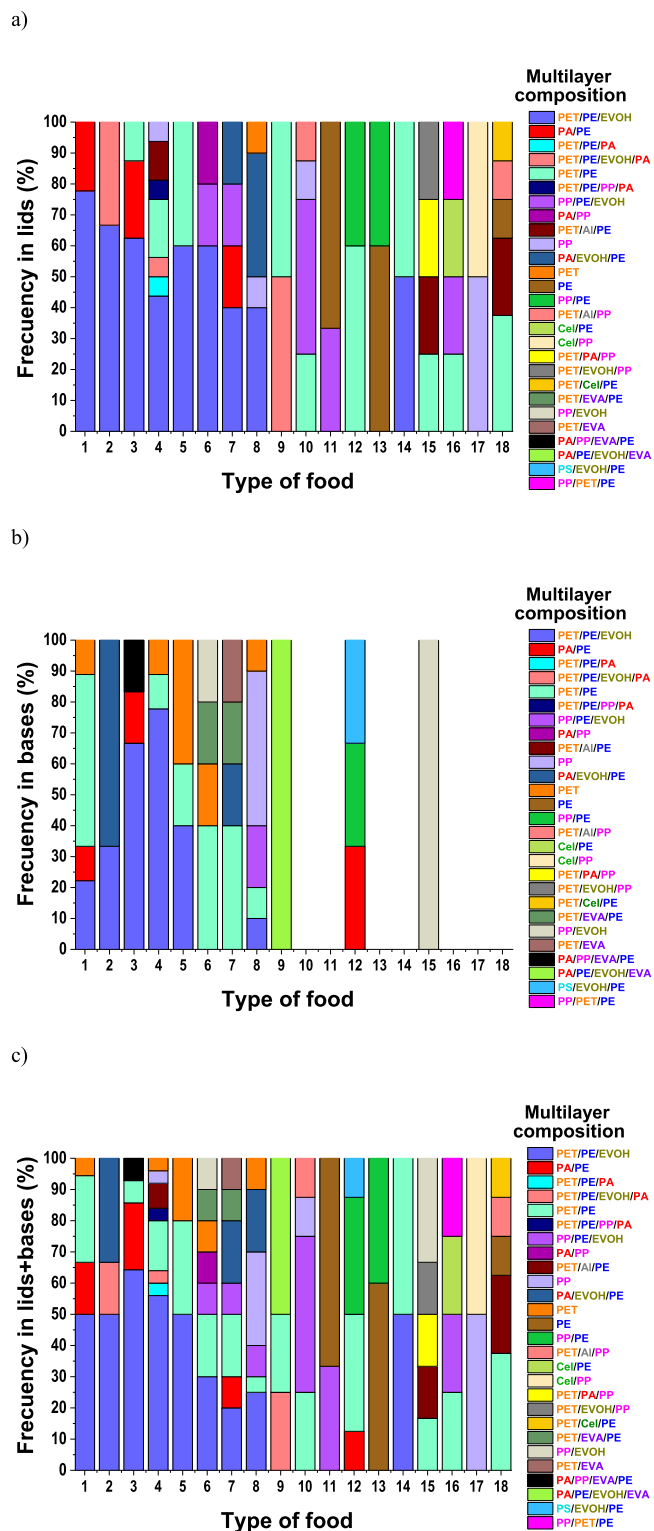


Fig. 3. Relative frequency distribution of the 27 multilayer film compositions across 18 food categories (Cel: cellulose-based materials). a) Distribution in lids, b) distribution in bases, c) distribution in food packages (lids+bases). Each stacked bar represents one food type, and the colored segments indicate the percentage of samples with a specific multilayer structure. Frequencies were normalized to 100% within each food category to highlight compositional trends.

steps. First, oxygen transmission rate (OTR) values reported in the literature were compiled for the packaging structures most frequently identified in our sample set, in order to illustrate the variability already described for similar food-packaging applications. Second, experimental OTR measurements were performed on a small subset of randomly selected commercial films to verify, under a single and uniform testing protocol, whether a similar dispersion could also be observed in real market samples.

Accordingly, after identifying the most frequent multilayer architectures by application ((a) processed meats, (b) cheese and cured meats, (c) chilled ready-to-eat meals, and (d) dry snacks), OTR values were compiled from the literature for those configurations. The purpose was not to benchmark the absolute barrier performance of each structure, but to examine whether materially different multilayer films used for similar applications converge towards comparable functional ranges. Sources, test conditions, and, when available, total or per-layer thickness are listed in Table S13 (SI, Section S5).

Fig. 4a-d summarizes the literature-reported OTR values for these four applications and includes orange lines indicating typical barrier requirements. The data show broad dispersion, often spanning one or more orders of magnitude within the same application. This variability reflects, at least in part, the coexistence of different functional requirements (e.g., gas barrier, mechanical resistance, light protection) and varying risk acceptance criteria across brand owners. As a result, laminates containing high-performance oxygen-barrier layers such as EVOH coexist with others relying on moderate gas-barrier materials such as PET or PA, and values are found both close to and far from the expected requirement range.

Part of this variability may be explained by differences in thickness, barrier-layer position, processing conditions, or test methodology among literature sources. In addition, packaging requirements are not defined by oxygen barrier alone, since moisture control, CO₂ retention, puncture resistance, thermal resistance, and light protection may also be relevant depending on the product. Thickness variation and barrier-layer continuity or position therefore complicate strict comparisons, and area-normalized OTR was retained in the main text, with permeance provided in the SI as a sensitivity analysis.

To allow direct comparison under a uniform protocol, OTR was measured in this work for five commercial films intended for the same application, namely processed-meat packaging. These samples were randomly selected from the analyzed set and tested under a common protocol. These measurements were not intended to provide OTR data for the full sample set, but rather to serve as a targeted experimental verification of the variability suggested by the literature analysis. The results are shown in Fig. 4e.

Despite having similar total thickness (around 61 μm), the five tested films showed a broad range of OTR values, reproducing the same general pattern observed in the literature. This indicates that even commercial packages designed for the same function and having comparable thickness may differ substantially in barrier performance. This effect is particularly relevant under the conditions used here (85% RH), which are demanding for EVOH-based structures and can amplify the influence of relatively small structural differences.

In addition to oxygen barrier, water vapor transmission rate (WVTR) is also relevant for moisture-sensitive products such as cereals, dehydrated snacks, battered frozen foods, or refrigerated products in which water exchange may affect texture and stability. As with OTR, literature-reported WVTR values also vary widely, even among similar multilayer systems, depending on formulation, thickness, and processing conditions (Robertson, 2016; Siracusa, 2012). Although WVTR was not experimentally measured in this work, the literature shows the same general trend: barrier performance can vary considerably among structures used for similar applications.

Taken together, the literature data (Fig. 4a-d) and the experimental verification performed in this work (Fig. 4e) show that, for a given set of functional requirements, the market offers multiple packaging solutions

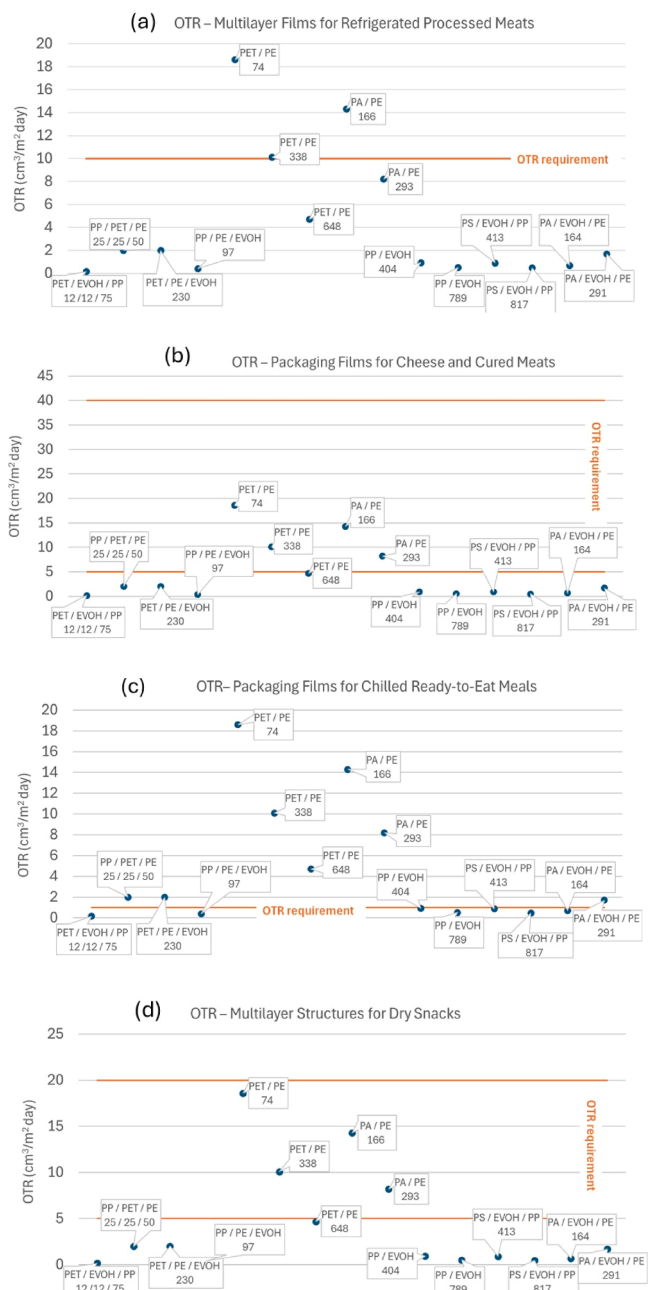


Fig. 4. Oxygen transmission rate (OTR) values of commercial multilayer films used in food packaging for four different applications-a) processed meats, b) cheese and cured meats, c) chilled ready-to-eat meals, d) dry snacks-based on experimental data extracted from previously published scientific literature (see Supporting Information for full references). Film thickness (μm), either total or by layer when available, has been included to aid interpretation, orange reference lines indicate typical OTR requirements for each application and e) five commercial packages for processed-meat products (randomly selected), showing film sketches and OTR values determined at 23°C and $85\% \text{ RH}$ (ASTM F1927-20), all films had similar total thickness ($\approx 100 \mu\text{m}$). For comparison purposes, literature and experimental OTR values are shown on an area-normalized basis; values reported as $\text{cm}^3 \text{ m}^{-2} \text{ day}^{-1}$ and $\text{cm}^3 \text{ m}^{-2} \text{ day}^{-1} \text{ atm}^{-1}$ are numerically equivalent when the oxygen partial-pressure difference is 1 atm.

with different levels of structural complexity and barrier performance. Some structures meet the expected functional requirements, while others fall above or below typical performance ranges. This variability indicates that similar functional outcomes can be achieved using materially distinct architectures. From a circularity perspective, such

diversity has direct implications for recyclability, as it often involves polymer combinations with different degrees of compatibility within conventional mechanical-recycling streams. While some combinations (e.g., PE/PP or PE/EVOH-based systems (Bartlett et al., 1982; Rodrigues et al., 2018; Seier et al., 2024)) may still yield moderate-quality recyclates, others (e.g., PET/PE (Pawlak et al., 2002; Uehara et al., 2015)) are more problematic and can significantly reduce the performance of recycled materials. These observations are consistent with established design-for-recycling guidelines (e.g., CEFLEX, RecyClass), which emphasize the importance of polymer compatibility and the avoidance of complex multilayer structures that hinder effective sorting and recycling. Overall, these results support the need for better alignment between functional requirements and material selection, as well as for more standardized packaging architectures that reduce unnecessary structural diversity.

4. Discussion: implications for circularity and policy alignment

The analysis of 163 commercial food-packaging films reveals an exceptionally high degree of structural and compositional diversity within the current European market, with forty-two distinct multilayer configurations and twenty-seven different polymer combinations identified. From a waste-management and circular-economy perspective, this level of heterogeneity has direct consequences for recyclability, as it results in a large number of materially incompatible structures that cannot be effectively sorted or processed within existing mechanical recycling streams. Rather than reflecting function-driven optimization, the observed diversity indicates that similar packaging requirements are being met through multiple, non-standardized material solutions, limiting economies of scale and undermining recycling efficiency. From a circular-economy perspective, this structural heterogeneity represents a fundamental inefficiency. Most multilayer films incorporate incompatible polymers, such as PET/PE or PA/PP/EVOH systems, which, when processed together in conventional recycling streams, result in recyclates with poor mechanical and functional properties (Adam et al., 2025; Möllnitz et al., 2021). As a result, these materials are commonly landfilled or incinerated despite being nominally recyclable under current classifications. The absence of clear correlations between structure, thickness, and function indicates that packaging design has evolved through incremental, uncoordinated decisions rather than through harmonized engineering principles.

The structural fragmentation identified in this study is particularly relevant in the context of the forthcoming EU Packaging and Packaging Waste Regulation (PPWR), which establishes that all packaging placed on the EU market should be recyclable by 2030. Within this framework, recyclability is defined not only in terms of design, but also in terms of effective collection, sorting, and recycling at scale, as well as the integration of recycled content. This implies compatibility with existing industrial recycling systems and sufficient material flows to ensure economically viable processing. In this context, the PPWR introduces recyclability performance criteria and classification systems, under which packaging that does not meet minimum recyclability thresholds (e.g., below 70%) may be restricted from the market. In addition, eco-modulation of extended producer responsibility (EPR) fees is expected to create economic incentives for packaging designs that are compatible with established recycling streams. While all analyzed packages comply with existing food-contact material (FCM) legislation, which governs safety and suitability for contact with food, the coexistence of numerous materially incompatible multilayer structures serving equivalent functions poses challenges for the implementation of the PPWR, which is focused on recyclability and circularity. These regulatory frameworks operate with different objectives, and their misalignment becomes particularly evident in highly fragmented material landscapes, where recyclability becomes a theoretical rather than a practical attribute. In such cases, effective recycling depends on the ability to sort materials into consistent streams and process them at sufficient scale. When

packaging structures are highly diverse and materially incompatible, these conditions are difficult to achieve, limiting recycling efficiency and the incorporation of recycled content. The results presented here indicate that, without improved compatibility between packaging structures and existing recycling streams, current market practices remain misaligned with the regulatory ambition of achieving circular packaging systems. In this context, the establishment of a clear legal basis at the European level may be necessary to enable coordinated action and avoid fragmented or conflicting implementation across stakeholders.

Furthermore, the lack of transparency regarding material composition, often associated with proprietary multilayer formulations, emerges as a critical barrier to effective waste sorting and recycling. The coexistence of structurally similar yet compositionally distinct laminates, as observed in this study, increases operational complexity for recyclers and limits the scalability of both mechanical and advanced recycling technologies. In practical terms, the observed structural diversity translates into inefficiencies across the packaging value chain, including increased design and procurement complexity for producers, reduced predictability for recycling operations, and diminished recovery efficiency at system level. From a circular-economy perspective, the results indicate that progress towards recyclable food packaging requires complementary design strategies. First, improving structural compatibility (by reducing the number of materially distinct multilayer configurations used for equivalent applications) would facilitate sorting and enable recycling at scale. However, during the transition towards more recyclable systems, both compatible and incompatible packaging structures are likely to coexist. In this context, the ability to distinguish between materials within mixed waste streams becomes critical. Approaches such as material identification markers or coding systems could support sorting processes and improve recycling efficiency. Second, functional benchmarking, based on realistic barrier-performance requirements for specific food categories, would help avoid unnecessary material complexity and over-design. Together, these approaches directly address the structural fragmentation documented in this work.

Overall, this study highlights that achieving circularity in food packaging is not solely dependent on the development of new recyclable materials (e.g., novel polymer formulations or bio-based alternatives), but also on rationalizing the existing structural landscape. The empirical mapping presented here demonstrates that market-driven diversity without functional justification undermines eco-design principles and delays the transition towards circular packaging systems envisioned by the European Green Deal. By providing quantitative evidence of structural redundancy, this work offers a data-driven basis to inform regulatory implementation, guide industrial harmonization, and support the design of future packaging architectures aligned with circular-economy objectives.

5. Conclusions

This study provides quantitative evidence of the structural fragmentation currently present in food-packaging films available on the European market. The analysis of 163 commercial samples identified 42 distinct multilayer configurations and 27 different polymer combinations, with no systematic relationship between material structure, film thickness, and functional application. These results demonstrate that equivalent packaging functions are routinely achieved through a wide range of materially incompatible architectures.

While the analyzed packaging solutions comply with food-contact material (FCM) legislation, their structural diversity and material incompatibility pose significant challenges for achieving the recyclability targets established under the PPWR. This highlights a broader misalignment between food-safety requirements and circular-economy objectives, which remains a key barrier to the implementation of scalable recycling systems. In particular, the persistence of numerous functionally redundant multilayer structures represents a systemic

barrier to efficient sorting, recycling at scale, and the incorporation of recycled content.

Overall, the findings indicate that advancing towards circular food packaging requires not only the development of new recyclable materials, but also the rationalization of existing packaging architectures. Reducing unnecessary structural diversity and aligning material design with realistic functional requirements emerge as key conditions for enabling scalable recycling systems and achieving regulatory circularity targets.

CRediT authorship contribution statement

Alba Torija-López: Formal analysis, Data curation. **Karina C. Núñez-Carrero:** Writing – original draft, Visualization, Validation, Methodology, Investigation. **Carlos Sedano:** Formal analysis, Data curation. **Miguel Ángel Rodríguez:** Visualization, Validation. **Saúl Vallejos:** Validation, Methodology, Funding acquisition, Conceptualization. **Miriam Trigo-López:** Writing – original draft, Visualization, Validation, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.resconrec.2026.109025](https://doi.org/10.1016/j.resconrec.2026.109025).

Additional analysis regarding the characterization of the materials (SEM, FTIR, TGA, DSC, mechanical performance, thickness, and composition), can be found in the electronic Supplementary Information (SI).

Data availability

Open Data is available at <https://riubu.ubu.es/handle/10259/5684> under the name “UBU-Polymers Research Group 27052026”.

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