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# Research on the manufacture and environmental assessment of vibration and structure-borne sound insulation foams from packaging film waste

L.E. Alonso-Pastor [a,*,1], M.A. Morcillo [b], E. Laguna-Gutiérrez [c], P. Baños [d], J. García [d], J.L. Moreno [d], M.A. Rodríguez-Pérez [a], K.C. Núñez Carrero [a,*]

[a] Department of Condensed Matter Physics, CellMat Laboratory, University of Valladolid, Paseo de Belén, 7, Valladolid 47011, Spain
[b] Foundation for Research and Development in Transport and Energy (CIDAUT), Parque Tecnológico de Boecillo, Plaza Vicente Aleixandre Campos 2, Valladolid 47051, Spain
[c] CellMat Technologies S.L, C. del Argón, 1, Valladolid 47012, Spain
[d] The Circular Lab, Ecoembes, Parque Municipal de Jardinería, Carretera del Cristo, 15, Logroño 26005, Spain

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ABSTRACT

This study investigates the manufacture and environmental assessment of acoustic insulation foams made from recycled polyethylene (RM) from packaging film waste. Blends of RM with virgin polyethylene (PE) and ethylene-vinyl acetate (EVA) were used to produce cellular structures through chemical (Ch) and physical (Ph) foaming processes. The aim was to develop materials with properties comparable to commercial acoustic insulation products in construction sector, assessing structural integrity and acoustic performance via dynamic stiffness. Products with performance like the commercial were achieved with recycled content ranging from 40 to 80 wt%. These successful cases were also evaluated for environmental impact. The life cycle assessment considered two approaches: one analysing the production of 1 kg of foam (standardized density values), where physical foaming showed a lower environmental footprint, and the other evaluating the mass needed to achieve the dynamic stiffness of the commercial reference (empirical density values), which favoured chemical foaming for producing foams with comparable properties but lower densities. Although physical foaming has environmental advantages, the higher densities achieved with RM limit its viability. Consequently, chemical foaming is more environmentally favourable due to lower material consumption. Therefore, Ch_RM:EVA,80:20 is optimal for technical requirements, while Ch_RM:PE,40:60 is more environmentally advantageous. The compromise solution that addresses both technical and environmental aspects is Ch_RM:EVA,40:60. This foam showed acoustic performance equivalent to the commercial, achieved through a manufacturing process and recycled content minimizing environmental impacts. Furthermore, transforming packaging waste into a long-lasting product also reduces waste accumulation and delays non-sustainable but necessary processes like energy generation.

## 1. Introduction

One of the most crucial challenges currently facing the plastic sector is the pressing need to address the unsustainable nature of the linear economy -which we already know has significant environmental consequences like pollution, climate change and resource depletion- to a sustainable model where development and growth optimize the use of available resources, reduce the consumption of raw materials, and recover waste [1,2]. This issue is particularly pronounced in the packaging sector, which accounts for approximately 40 % of total plastic usage worldwide [3–6]. Within the linear economy model, packaging consumption presents a unique environmental challenge, as it involves the consumption of massive quantities of material in products with short lifetimes. Consequently, there is a notable consumption of non-renewable fossil fuels and a considerable generation and accumulation of waste. Moreover, packaging materials, often lightweight, like films, can be inadvertently dispersed by natural elements like wind or water currents, leading to their uncontrolled spread worldwide. This

* Corresponding authors.
*E-mail addresses:* luiseduardo.alonso@uva.es (L.E. Alonso-Pastor), karinacarla.nunez@uva.es (K.C. Núñez Carrero).
[1] Current address: Department of Manufacturing Process Engineering, School of Industrial Engineering, University of Valladolid, Paseo del Cauce, 59, 47011, Valladolid, Spain

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combination of factors leads to significant environmental impact. Compounding the issue, plastic consumption in the packaging sector is expected to increase in the coming decades [7].

Transitioning to a circular economy is therefore necessary, but given the importance and magnitude of this sector, implementing such a significant change is not straightforward. To meet this challenge, two approaches are being considered: preventive, which aims to avoid damage (e.g. bio-based, compostable), and curative, which focuses on treating accumulated waste.

As for the curative approach, the different recycling technologies and processes can be grouped into four categories: primary, secondary, tertiary, and quaternary. In primary and secondary plastic recycling, the material is recovered and reused (the difference being the quality of the recycled product), while in tertiary and quaternary recycling, it is converted into smaller molecules or energy [8,9]. The product of tertiary recycling can be used as feedstock to produce new polymers and composites [9–11], valuable chemicals [9–12], or fuel [12,13]. Quaternary recycling can be used directly to generate electricity. [13,14] The product of primary and secondary recycling processes can be used alone or blended with virgin polymers in specific proportions for the manufacture of products, whether for the original purpose or for other uses [8,9]. However, these recycling methods face limitations, particularly with packaging products, where the main issue is that they are generally in the form of films, making them difficult to process, and composed of multiple polymers, leading to heterogeneous mixtures [15]. This is particularly relevant for polyethylene (PE), which is the most widely consumed polymer in the packaging sector [16–20]. PE from the packaging products can be recycled through mechanical recycling, a process that involves collection, sorting, washing, extrusion, and reprocessing of the material [21–23]. However, this approach presents nowadays significant limitations. It is known that recycled PE undergoes thermal and mechanical degradation throughout processing cycles, which negatively affects its properties. But there are also other complications inherent in product packaging. Eriksen et al. studied thermal degradation, processability and mechanical properties of PE re-extruded from post-consumer waste. In this work, it is highlighted that the quality of reprocessed PE samples is highly dependent on the impurities of other polymers [24]. Given the limitations, alternatives are proposed, and chemical recycling has emerged as a potential solution. However, in the case of PE, this approach remains a technology under investigation and presents significant technical complexity. Unlike other polymers, such as polyethylene terephthalate (PET), which can be chemically recycled due to the presence of ester groups that facilitate depolymerization, PE lacks these functionalities in its molecular structure, making chemical recycling more challenging [25,26]. Despite this, some progress has been made in this field. For instance, Arroyave et al. demonstrated advances in the catalytic dehydrogenation of high-density polyethylene (HDPE), using iridium-based catalysts (Ir-POCOP), allowing for the repolymerization of PE chains [26]. However, these technologies are not yet ready for large-scale application and require further research and development. Due to the challenges in both mechanical and chemical recycling of PE packaging products, a large portion of post-consumer plastic waste ends up being incinerated, sent to landfills, or, worse, dispersed in the environment. This situation underscores the urgent need to develop sustainable solutions to manage the growing volume of packaging products in the coming decades [7].

In recent years, several studies have proposed solutions to manage post-consumer PE waste by transforming it into foams. For instance, Bawareth et al. addressed the challenges of recycling crosslinked polyethylene (XLPE) by using plastic particle size control and urethane-based foam engineering, aiming to optimize thermal properties, mechanical integrity, manufacturing scalability, and cost-efficiency. They produced foamed composites that retained mechanical robustness, exhibited higher thermal resistance, and improved diffusivity, demonstrating RPUF/XLPE foaming strategies as a simple and cost-efficient method to recycle XLPE for thermal applications [27]. Lyapidevskaya et al. studied low-density foams with 15–25 % recycled LDPE content, showing that an optimal 20 % incorporation resulted in materials nearly identical in properties to virgin foam PE while reducing production costs by 12–15 %. These modified foams were suitable for vapor, heat, and waterproofing applications, including insulation systems for household objects and floating floors [28]. Semenov et al. also focused on foamed LDPE for construction, demonstrating that 20–25 % recycled content produced materials with preserved thermal, vapor, and waterproofing properties, enabling seamless insulating shells, reducing cost by 8–12 %, and lowering the environmental footprint associated with waste storage [29]. While these studies demonstrate that technically viable products can be obtained from post-consumer PE waste, the environmental viability of the proposed solutions is not fully assessed. Considering that the goal is to provide an alternative product that also addresses environmental challenges, this is an important aspect, as incorporating a recycled material does not necessarily guarantee a reduction in environmental impact and therefore may not fully address the fundamental problem of sustainability.

This issue is of great importance today, as there are growing environmental demands and sustainability requirements. The shift towards a circular economy introduces new challenges, particularly in ensuring that recycling and reuse processes are not only technically viable but also environmentally beneficial. While recycling is often seen as a solution, it involves additional processes that may not always reduce environmental impact, and in some cases, can even exacerbate it. Therefore, it is necessary to assess the environmental implications of recycling methods, using tools like Life Cycle Assessment (LCA), in order to accurately evaluate their true sustainability and effectiveness in mitigating environmental impacts.

In the circular economy, LCA emerges as a standardized, internationally recognized tool [30,31] that allows for the rigorous and consistent quantification of the environmental impact of a product, process, or service across all its stages, from raw material extraction to final disposal [30–33]. LCA provides reliable and consistent results, facilitating informed decision-making to enhance sustainability. In the field of PE film waste recycling, LCA has been used to determine and compare the environmental impact of various developments. For example, López et al. reviewed LCA studies concerning bags and their end-of-life treatments. They concluded that, in terms of end-of-life treatments, recycling of these products had the least environmental potential impacts, followed by energy recovery, and finally, landfilling [34]. Chen et al. applied the LCA approach to evaluate the environmental impacts of mechanical recycling, incineration, and landfilling of waste plastics. Among the three treatments, mechanical recycling showed overwhelming advantages over incineration and landfilling due to the significant environmental benefits resulting from the replacement of virgin plastics [35]. Horodytska et al. reviewed plastic films waste management technologies from two different sources: post-industrial and post-consumer. The LCA studies review led to the conclusion that mechanical recycling should be the preferred option for plastic waste treatment when the quality of the recycled material is good enough. The non-recyclable fraction should be sent to energy recovery with electricity production and district heating or used as refuse-derived fuels [23]. Martín-Lara et al. applied the LCA methodology to quantify the environmental impacts associated to the production of 1 kg of recycled LDPE pellets. They concluded that mechanical recycling of plastic waste can be considered a sustainable waste management practice; however, this treatment also generates an environmental impact that must be taken into account [36]. Bataineh et al. evaluated the environmental impacts of mechanical recycling of the postconsumer high-density polyethylene (HDPE) and polyethylene terephthalate (PET). They compared the Life Cycle Assessment (LCA) results with the eco-profile of virgin PET flakes and HDPE pellets, and their analysis concluded that recycling PET and HDPE offers significant environmental benefits over single-use virgin materials, ultimately improving eco-efficiency [37]. Hence, according to the results of the LCA, mechanical recycling, as long

as it results in a product of sufficient quality, emerges as the most environmentally advantageous recycling method.

From a technical point of view, there are still significant challenges in improving mechanical recycling to manage the growing volume of plastic waste, especially in the packaging sector. However, LCA indicates that mechanical recycling remains the best option for sustainability. In this context, this work addresses systematically the transformation of PE films from packaging waste into an acoustic insulation product for the building and construction sector.

Several kinds of materials are used to achieve soundproofing in buildings. It can be distinguished those that act directly on sound pressure waves, either preventing the air borne (insulating acoustic materials) or avoiding reflections (absorbent materials). However, other materials are used to isolate the structure-borne. The energy is transmitted through the solid medium by means of vibrations, for example impacts from footsteps or falling objects, or vibrations from machinery located near the foundations. To minimize this energy transfer, elastic materials with controlled stiffness are used in the constructions. These systems act as a low-pass filter and reduce the passage of energy in the high-frequency band. The cut-off frequency from which these materials begin to work is established directly from the dynamic rigidity of the insulating element and the mass placed on top (mass of the slab or the wall). Different building regulations establish control of the dynamic stiffness of materials. The standard that regulates this characterization is ISO 9052–1 [38].

The aim of the research, therefore, is not only to use this waste but also to add value to it, transforming it from a short-lived product (days, weeks) into a long-lasting (years) technical product. This work advances the circular use of plastics by transforming real, post-consumer polyolefin film mixtures into floating-floor underlay foams via two scalable routes—chemical foaming with azodicarbonamide (ADCA) and $CO_2$ gas-dissolution foaming—and by quantitatively linking structure–property–impact. Unlike most prior studies on recycled plastics for acoustics, we (i) use heterogeneous, industrial waste streams rather than model recyclates, (ii) validate dynamic stiffness following ISO 9052–1 against a commercial underlay, and (iii) perform an ISO 14040/44-compliant LCA with a performance-based functional unit that equalizes dynamic stiffness to the benchmark. The resulting pilot-scale prototype (TRL 6 technology demonstrated in a relevant environment) achieves equivalent vibration isolation at lower environmental burdens. To this end, both the development of the manufacturing process and the evaluation and decision-making through LCA were addressed. The residue was mechanically recycled and then upcycled into a low-density foam product for noise insulation with the same features -structural integrity and insulation- as commercial analogues used for flooring in construction. Different virgin materials – PE and EVA- and foaming techniques -chemical and physical- where considered. The successful cases were analysed through LCA to assess their sustainability viability and to identify and justify the preferred option, as well as the strategies for improvement.

The manuscript is structured into three main sections: Experimental, Results and Discussion, and Conclusions. The Experimental section contains all information on materials, methods, and procedures used, and describes the LCA following the ISO 14040 framework. The Results and Discussion section is divided into two parts. The first part focuses on the manufacture of acoustic insulation foam from packaging film waste, including the study of materials, processing, and foaming, and evaluating the final product to draw conclusions based on technical criteria. The second part presents the LCA results, relating environmental impacts to the technical aspects of the foams and identifying a compromise solution that balances technical performance and environmental impact. Finally, the Conclusions section summarizes the main points and the key results.

## 2. Experimental section

### 2.1. Materials

Waste PE films from packaging products were provided by Ecoembes (Spain). These films come from the yellow container, which in Spain is designated for the selective collection of plastic packaging, briks and cans [39], and represent the discarded fraction of a selection plant of sorting rejects due to their low density, separated using fans. Table 1 shows the composition of the recycled material utilized in this investigation, as provided by the supplier and confirmed by infrared spectroscopy (IR). It is important to highlight that the composition of recycled materials varies from one batch to another. Each batch comprises a series of residual products that influence its composition. Consequently, all experiments were conducted using the same batch.

Raw polymers used for blending were a Low-Density Polyethylene (PE) 410E from The Dow Chemical Company, which has a solid density of 0.925 g/cm$^3$ and a melt flow index of 2 g/10 min (190 ºC, 2.16 kg), an Ethylene copolymer resin Entira EP1753 from DuPont Company, which has a solid density of 0.95 g/cm$^3$ and a melt flow index of 3 g/10 min, used as compatibilizer, and an Ethylene-Vinyl Acetate copolymer (EVA) Elvax 265 A from DuPont Corporation, which has a solid density of 0.95 g/cm$^3$ and a melt flow index of 3 g/10 min (190 ºC, 2.16 kg).

Polymer matrices were chemically cross-linked with Dicumyl Peroxide (DCP) (99 %) from Acros Organics. Additional information on crosslinking is provided in Supplementary Information S1.

Azodicarbonamide (ADCA) Unifoam AZ VI-50 from Hebron S.A and Zinc Oxide (ZnO) from Sigma-Aldrich were used as Chemical Blowing Agent (CBA) and catalyser of this CBA, respectively. On the other hand, Carbon Dioxide in supercritical state ($scCO_2$) from Air liquid were used as Physical Blowing Agents (PBA).

The commercial acoustic insulation foamed product, used as reference, was a flexible cross-linked PE sheet for impact noise insulation, marketed under the trade name Impactodan by Danosa. Table 2 groups the main characteristics of this product within the scope of this study.

### 2.2. Methods

#### 2.2.1. Recycled material (RM) obtainment

The waste was washed with a basic aqueous solution, dried and extruded at 230 ºC (nozzle temperature) and 120 rpm in a twin screw co-rotating extruder (L/D=52) with a capacity of one Tn per hour. This homogenized material was used to prepare the blends and has been identified as recycled material (RM).

#### 2.2.2. Blends composition and obtainment

RM was mixed with virgin polymers to adjust its rheological behaviour. Two groups of blends were prepared. Blends with PE (RM:PE): the recycled material was blended with the PE and the Ethylene copolymer resin (compatibilizer) and blends with EVA (RM:EVA): the recycled material was also blended with the EVA copolymer. Table 3 shows the samples prepared.

Blends were prepared by extrusion in a co-rotating twin extruder, model Leistritz 27 GL (L/D=36). The extrusion conditions for the above-described blends were 230 ºC (nozzle temperature) and 100 rpm for RM:PE, and 150 ºC (nozzle temperature) and 100 rpm for RM:EVA blends.

**Table 1**
Composition of the waste packaging films.

| Polymer | Weight fraction |
|---|---|
| Low-density Polyethylene | 0.59 ± 0.02 |
| High-density Polyethylene | 0.14 ± 0.03 |
| Polypropylene | 0.14 ± 0.01 |
| Polyamide | 0.09 ± 0.04 |
| Others | 0.04 ± 0.01 |

**Table 2**
Main characteristics of the commercial product used as reference.

| Reference commercial product | | | |
|---|---|---|---|
| Polymer | **PE** | Density | **27 kg/m$^3$** |
| Cross-linked | **Yes** | Type | **Closed** |
| Thickness | **2 mm** | Dynamic stiffness | **173.2 MN/m$^3$** |

**Table 3**
Range of blends prepared. Quantities are reported in % by weight.

| **RM:PE blends** | | | | **RM:EVA blends** | | |
|---|---|---|---|---|---|---|
| **Sample name** | **RM** | **PE** | **Compat.** | **Sample name** | **RM** | **EVA** |
| RM:PE, 90:10 | 90 | 10 | - | RM:EVA, 90:10 | 90 | 10 |
| RM:PE, 80:20 | 80 | 10 | 10 | RM:EVA, 80:20 | 80 | 20 |
| RM:PE, 60:40 | 60 | 30 | 10 | RM:EVA, 60:40 | 60 | 40 |
| RM:PE, 40:60 | 40 | 50 | 10 | RM:EVA, 40:60 | 40 | 60 |
| RM:PE, 20:80 | 20 | 70 | 10 | RM:EVA, 20:80 | 20 | 80 |

### 2.2.3. Foaming

Two different foaming processes were considered:

*2.2.3.1. Chemical foaming (Ch).* Incorporation of the different reagents (DCP, ADCA and ZnO) took place in two steps. ZnO was incorporated firstly by extrusion (190 ºC - 100 rpm for RM:PE and 150 ºC – 100 rpm for RM-EVA) in the same extruder already described. The resulting pellets were dried in a convection oven at 80 ºC for 6 h before further processing. In a second step, ADCA and DCP were mixed with the previous pellets by a soft extrusion: 120 ºC and 60 rpm; for all blends. Soft conditions were needed in order to avoid reagents activation (see Table 4). After that, solid precursors for foaming were produced by compressing moulding the polymeric blends in a hot plates press, model Schwabenthan Polystat 200 t, at 120 ºC for both groups of blends.

The solid precursors were foamed by one-step compression moulding technique. Decomposition temperature of ADCA was adjusted (decreased) by adding ZnO depending on blend composition. Samples were cross-linked and expanded in one step by using a hot plate press.

In order to optimize the compression moulding technique for obtaining foams from the recycled material, several parameters were systematically varied, while others were kept constant. Foaming temperature ($T_f$), cross-linking agent content (X-agent) and ZnO content were varied, while the key parameters of the compression moulding process temperature ($T_{precursor}$) and time ($t_{precursor}$) to obtain the precursor, ADCA amount and compression time for foaming ($t_c$) were kept constant. Values of above-mentioned parameters are collected in Table 5.

The most successful foams were obtained by compressing for 5 min at 170 ºC for RM:PE blends and at 10 min at 150 ºC for RM:EVA blends and then releasing the pressure to promote the material expansion. The applied pressure during the compression step was 100 bar. Samples of 200 × 200 mm$^2$ were obtained, from which specimens for each characterization technique were taken.

*2.2.3.2. Physical foaming (Ph).* Polymer matrixes were cross-linked before foaming. DCP was incorporated to the polymeric blends by soft extrusion (120 ºC - 60 rpm). Cross-linking was carried out in a hot plate press. RM:PE blends were cross-linked at 170 ºC, while those with EVA at 150 ºC.

**Table 4**
Summary of the components and the chemical foaming process used.

| Step* | Reagents | Amount (pph) | | Function |
|---|---|---|---|---|
| | | RM:PE | RM:EVA | |
| 1 | Zinc Oxide | 5 | 10 | CBA activator |
| 2 | ADCA | 15 | | CBA |
| | DCP | 2 | | Cross-linking agent |

* All the compounds were incorporated by extrusion.

**Table 5**
Parameters and their values used for the optimization of compression moulding technique for obtaining foams form the recycled material (RM).

| Parameter | Set value | | | | | |
|---|---|---|---|---|---|---|
| **$T_{precursor}$** | 120 ºC | | | | | |
| **$t_{precursor}$** | 3 min | | | | | |
| **$T_f$** | 170 ºC | | 180 ºC | | 190 ºC | |
| **X-agent** | 2 pph | 3 pph | | 5 pph | | 10pph |
| **ZnO** | 5 pph | | | 10 pph | | |
| **CBA** | 15 pph | | | | | |
| **$t_c$** | 90 s | | | | | |

Here, the process optimization was carried out by varying the parameters saturation temperature ($T_s$), saturation pressure ($P_s$) and cross-linking (X-linking), while the gas used (gas) and the saturation time ($t_s$) were kept constant. Table 6 shows the values of each of these parameters.

Foams were produced in a pressure vessel using the one-step gas dissolution process. The foams were obtained using saturation pressures between 50 and 100 bar and saturation temperatures between 120 ºC and 140 ºC (depending on the composition of the blend). The saturation time was 40 min for all the experiments. Supercritical $CO_2$ ($scCO_2$) was used as a physical blowing agent (PBA). Samples of sizes 1 × 1 mm$^2$ and 100 × 100 mm$^2$ were obtained depending on the type of characterization.

As a summary, Figure 1shows an overview of all processes. Fig. 1(a) represents the overall process, and Fig. 1(b) shows the various combinations that were conducted and evaluated based on technical and environmental criteria.

### 2.2.4. Characterization techniques

*2.2.4.1. Infrared spectroscopy.* Composition of the wasted material and the commercial foam was determined by Infrared Spectroscopy (IR). The IR spectra were taken at a resolution of 4 cm$^{-1}$ and 32 scans, using a Bruker Tensor 27 spectrometer.

*2.2.4.2. Extensional rheology.* Foaming ability of the different materials were determined by extensional rheology. Extensional viscosity of prepared blends was measured with a controlled-stress rheometer (AR 2000 EX, TA Instruments) with an accessory to measure extensional viscosity (SER 2, Xpansion Instruments). Tests were carried out at a fixed temperature of 160 ºC and at three different Hencky strain rates: 0.5, 1.0 and 2.5 s$^{-1}$. For each material, five samples were tested to ensure reproducibility.

From the extensional viscosity curves, the Strain Hardening (SH) as a function of time was calculated using Eq. (1):

$$SH(t,\dot{\varepsilon}) = \frac{\eta_E(t,\dot{\varepsilon}_H)}{\eta_{E0}(t)} \quad (1)$$

where $\eta_E(t,\dot{\varepsilon}_H)$ is the transient extensional viscosity as a function of time ($t$) and Hencky strain rate ($\dot{\varepsilon}_H$) and $\eta_{E0}(t)$ is the transient extensional viscosity in the linear viscoelastic regime, which can be determined in

**Table 6**
Values of the different parameters used for the optimization of the gas dissolution foaming technique to obtain foams from the recycled material.

| Parameter | Set value | | | |
|---|---|---|---|---|
| **$T_s$** | 120 ºC | 140 ºC | | 160 ºC |
| **$P_s$** | 50 bar | | 100 bar | |
| **X-linking** | Yes | | No | |
| **gas** | $CO_2$ | | | |
| **$t_s$** | 40 min | | | |

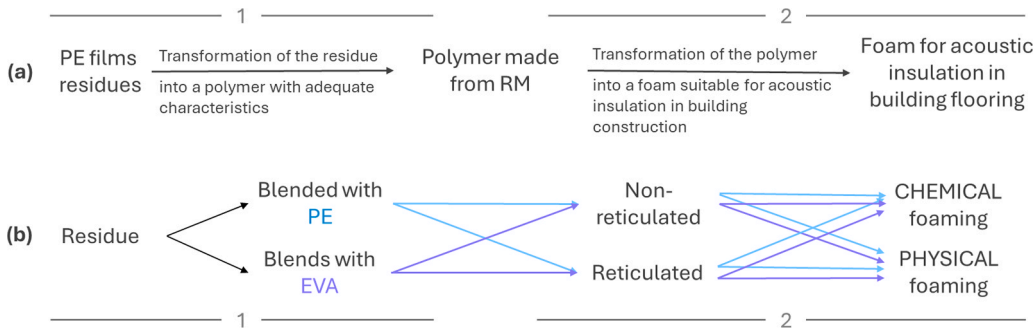


**Fig. 1.** Schematic representation of (a) global process and; (b) combination assessed.

two different but equivalent ways: as three times the growth curve of the transient shear viscosity at a very low speed or by extrapolating the superimposed portion of the extensional curves at different strain rates.

In order to carry out extensional rheology tests, solid density and melt density are needed, which were determined by gas picnometry (see section Density) and melt flow index measurements, respectively.

*2.2.4.3. Melt Flow Index measurements.* The mass flow index (MFI) and volumetric flow index (VFI) of different materials at a temperature of 160 °C have been determined using a mass of 2.16 kg, in a Atsfaar model TWELV index device. For each material, three measurements were carried out. The ratio between the two values (MFI/VFI) values has been used to determine the melt density of the different polymer matrixes at the temperature at which the extensional rheological tests are done.

*2.2.4.4. Density.* The solid density of the polymer matrices was determined by gas pycnometry using a gas pycnometer AccuPyc II 1340, Micromeritics. The foams density was measured by means of the Archimedes principle. Measurements were performed with the density determination kit for Mettler Toledo analytical balance, model AX205 DR, according to ISO 1183–1. Five samples per material were measured to ensure reproducibility.

*2.2.4.5. Differential Scanning Calorimetry (DSC).* Melting temperatures of polymers were measured by differential scanning calorimetry (DSC) with a Mettler Toledo DSC 851e. Temperature ranges from 25 to 200 ºC at a heating rate of 20 ºC $min^{-1}$ under nitrogen flow. Thermograms can be found in the Supplementary Information S2.

*2.2.4.6. Scanning Electron Microscopy (SEM).* SEM was used to observe characteristics of cellular structure such as cell size, cell density and cell anisotropy.

Foams were cooled using liquid Nitrogen to be able to cut them without modifying their structure. A FESEM Hitachi H-7000 microscope was used. For testing, samples were vacuum coated with a thin layer of gold-palladium alloy (Au-Pd) to make them conductive.

*2.2.4.7. Cell size and anisotropy.* From SEM micrographs the average cell size and the average cell anisotropy were determined. The cell size is defined as the average diameter of the cells in 3D. According to ASTM D3576 [40], the 3D cell size was obtained from the 2D cell size by multiplying the 2D measurement by 1.279. The anisotropy rate was calculated as the ratio between the length of the cells in the foam growth direction divided by the corresponding length in the perpendicular direction.

*2.2.4.8. Noise insulation characterization.* To evaluate impact noise insulation capacity of obtained foams and the commercial product, dynamic stiffness ($S_{dyn}$) was measured. Dynamic stiffness determines the vibration-transmitting insulation capacity of a material. The lower the dynamic stiffness value, the lower the frequency from which the insulation starts to be effective. Therefore, a product with a low dynamic stiffness value will be more effective as a mass-spring-mass system in a floating floor. This characteristic is important for determining the impact noise insulation, or for flank losses that contribute to airborne noise insulation. The units of dynamic stiffness are $MN/m^3$ obtained according to ISO 9052–1 [38].

The test consists of measuring the resonance frequency of a one-dimensional mass-spring system. The spring corresponds to the test specimen and the mass corresponds to an auxiliary element with a known mass within the specimen's working value. From the resonance frequency measured in the test using an accelerometer, the dynamic stiffness of the specimen to be characterized can be extracted. A high-capacity electrodynamic exciter, a dynamic signal acquisition system from Siemens (LMS Test Lab) and two piezoelectric accelerometers from PCB were used for its characterization. Further details on the test and the equipment used are provided in the Supplementary Information S3. Tests were performed according to ISO 9052–1 standard. $S_{dyn}$ was determine for different load ratings (90, 140, 330 and 510 $kg/m^2$) and for an excitation frequency ranging between 5 and 2000 Hz.

### 2.3. Life cycle assessment (LCA)

#### 2.3.1. Goal and scope

The goal of the LCA is to serve as a decision-making tool for selecting the most viable recycling process, considering environmental criteria in addition to technical criteria. Since this study focuses on using a waste material, meeting the technical requirements of the product alone is not sufficient. It is also necessary to consider the environmental impact of the entire process. To meet this goal, this study quantifies and analyses the potential environmental impacts of different transformation processes of PE film waste to obtain a product comparable to the commercial one. The study evaluates the use of different polymers (PE and EVA), different foaming processes (chemical and physical), and products with varying characteristics (density and dynamic stiffness). The LCA provides a comprehensive evaluation of the system, allowing for a more informed decision.

#### 2.3.2. Functional unit

Two functional units were considered. One was proposed to standardize significant increases or reductions in mass due to differences in the densities of the obtained foams (see Table 7). The other was a comprehensive analysis of the system based on empirical data. These functional units were: (i) the production of 1 kg of a foam with a density of 65 $kg/m^3$, and (ii) the production of a foam with the required mass to achieve the dynamic stiffness of the commercial reference product used as acoustic insulation in floor applications in building construction under ISO 9052–1 standard, Table 7 groups the scenarios considered (Table 8).

#### 2.3.3. System boundaries

The LCA system, established as a cradle-to-gate system, is showed in

**Table 7**
Empirical properties of the foams and the mass required to meet the functional unit.

| Scenario* | Density ($kg/m^3$) | Dynamic stiffness ($MN/m^3$) | Mass required (kg) |
|---|---|---|---|
| Ch_RM:PE,40:60 | 65 | 189.5 | 59.4 |
| Ch_RM:EVA,80:20 | 106 | 174.6 | 105 |
| Ch_RM:EVA,40:60 | 65 | 176.7 | 66.3 |
| Ph_RM:PE,60:40 | 91 | 139 | 183 |
| Commercial | 25 | 173.2 | 27 |

* Ch: Chemical foaming route; Ph: Physical foaming route; RM: Recycled material; PE: Virgin Polyethylene; EVA: Virgin Ethylene-Vinyl Acetate

Fig. 2. The system consists of (a) waste treatment, which includes the washing of the film waste and its transformation into a material that can be processed by industrial plastic transformation method (extrusion), (b) transformation of the residue into a polymer including its processing and blending with virgin plastics to achieve suitable rheological behaviour and properties, (c) chemical foaming of PE blends, which encompasses the foaming process of the material with a chemical blowing agent (ADCA), (d) chemical foaming for EVA blends, which involves the foaming process with ADCA in the material containing EVA, (e) physical foaming for PE blends, which involves the foaming process using a physical blowing agent ($CO_2$) and, (f) physical foaming for EVA blends, which comprises the physical foaming process in the material with EVA. More details about the processes are provided in Section 3.

### 2.3.4. Life cycle inventory (LCI)

Table 6 shows the inventory corresponding to the described stages: waste treatment, blending, and foaming, which are divided into chemical and physical. The data on the recycled material, its treatment, and the foaming processes, both chemical and physical, are primary data. The data on the production of virgin polymers and the commercial foaming process are secondary data from the database of GaBi version 2022.2.

### 2.3.5. Scenarios

Five scenarios were examined in the LCA study. A commercially available product was used as the reference (scenario 0) and compared to the following:

- Ch_RM:PE, 40:60(scenario 1)
- Ch_RM:EVA, 80:20(scenario 2)
- Ch_RM:EVA, 40:60(scenario 3)

**Table 8**
Inputs and outputs of processes of waste treatment, blending and foaming, which includes chemical and physical.

| **WASTE TREATMENT** | | | | | |
|---|---|---|---|---|---|
| **WASHING & SHREDDING** | | **Ch_RM:PE,40:60** | **Ch_RM:EVA,80:20** | **Ch_RM:EVA,40:60** | **Ph_RM:PE,60:40** |
| **Input** | **Output** | | | | |
| Film waste [kg] | | 27 | 90,9 | 28,6 | 131 |
| Electricity [MJ] | | 13,3 | 44,9 | 14,1 | 64,5 |
| Water [kg] | | 40,6 | 137 | 43 | 196 |
| | Film waste shredded [kg] | 23,2 | 78,1 | 24,6 | 112 |
| | Waste [kg] | 3,74 | 12,8 | 4 | 19 |
| | Waste water [kg] | 40,6 | 137 | 43 | 196 |
| **EXTRUSION** | | **Ch_RM:PE,40:60** | **Ch_RM:EVA,80:20** | **Ch_RM:EVA,40:60** | **Ph_RM:PE,60:40** |
| **Input** | **Output** | | | | |
| Film waste shredded [kg] | | 23,2 | 78,1 | 24,6 | 112 |
| Electricity [MJ] | | 28,7 | 96,4 | 30,3 | 139 |
| | RM [kg] | 22,7 | 76,6 | 24,1 | 110 |
| | Waste [kg] | 0,463 | 1,57 | 0,492 | 2,24 |
| **BLENDING** | | | | | |
| **FORMULATION** | | **Ch_RM:PE,40:60** | **Ch_RM:EVA,80:20** | **Ch_RM:EVA,40:60** | **Ph_RM:PE,60:40** |
| **Input** | **Output** | | | | |
| RM [kg] | | 22,7 | 76,6 | 24,1 | 110 |
| PE [kg] | | 28,4 | - | - | 54,9 |
| Compatibilizer [kg] | | 5,68 | | - | 18,3 |
| EVA [kg] | | - | 19,1 | 36,2 | - |
| | RM:PE [kg] | 56,8 | - | - | 183 |
| | RM:EVA [kg] | - | 95,7 | 60,3 | - |
| **EXTRUSION** | | **Ch_RM:PE,40:60** | **Ch_RM:EVA,80:20** | **Ch_RM:EVA,40:60** | **Ph_RM:PE,60:40** |
| **Input** | **Output** | | | | |
| RM:PE [kg] | | 56,8 | - | - | 183 |
| RM:EVA [kg] | | - | 95,7 | 60,3 | - |
| Electricity [MJ] | | 70,1 | 118 | 74,4 | 226 |
| | RM:PE [kg] | 55,6 | - | - | 180 |
| | RM:EVA [kg] | - | 93,8 | 59,2 | - |
| | Waste [kg] | 1,14 | 1,91 | 1,20 | 3,67 |
| **FOAMING** | | | | | |
| **CHEMICAL FOAMING FORMULATION** | | **Ch_RM:PE,40:60** | **Ch_RM:EVA,80:20** | **Ch_RM:EVA,40:60** | **Ph_RM:PE,60:40** |
| **Input** | **Output** | | | | |
| RM:PE [kg] | | 55,6 | - | - | - |
| RM:EVA [kg] | | - | 93,8 | 59,2 | - |
| ADCA [kg] | | 2,83 | 9,55 | 6,02 | - |
| DCP [kg] | | 0,973 | 1,66 | 1,05 | - |
| Electricity [MJ] | | 73,3 | 130 | 81,8 | - |
| | RM:PE formulated (ch)[kg] | 59,4 | - | - | - |
| | RM:EVA formulated (ch) [kg] | - | 105 | 66,3 | - |
| **PHYSICAL FOAMING** | | **Ch_RM:PE,40:60** | **Ch_RM:EVA,80:20** | **Ch_RM:EVA,40:60** | **Ph_RM:PE,60:40** |
| **Input** | **Output** | | | | |
| RM:PE [kg] | | - | - | - | 180 |
| DCP [kg] | | - | - | - | 3,49 |
| Electricity [MJ] | | - | - | - | 76,1 |
| | RM:PE formulated (ph) [kg] | - | - | - | 183 |

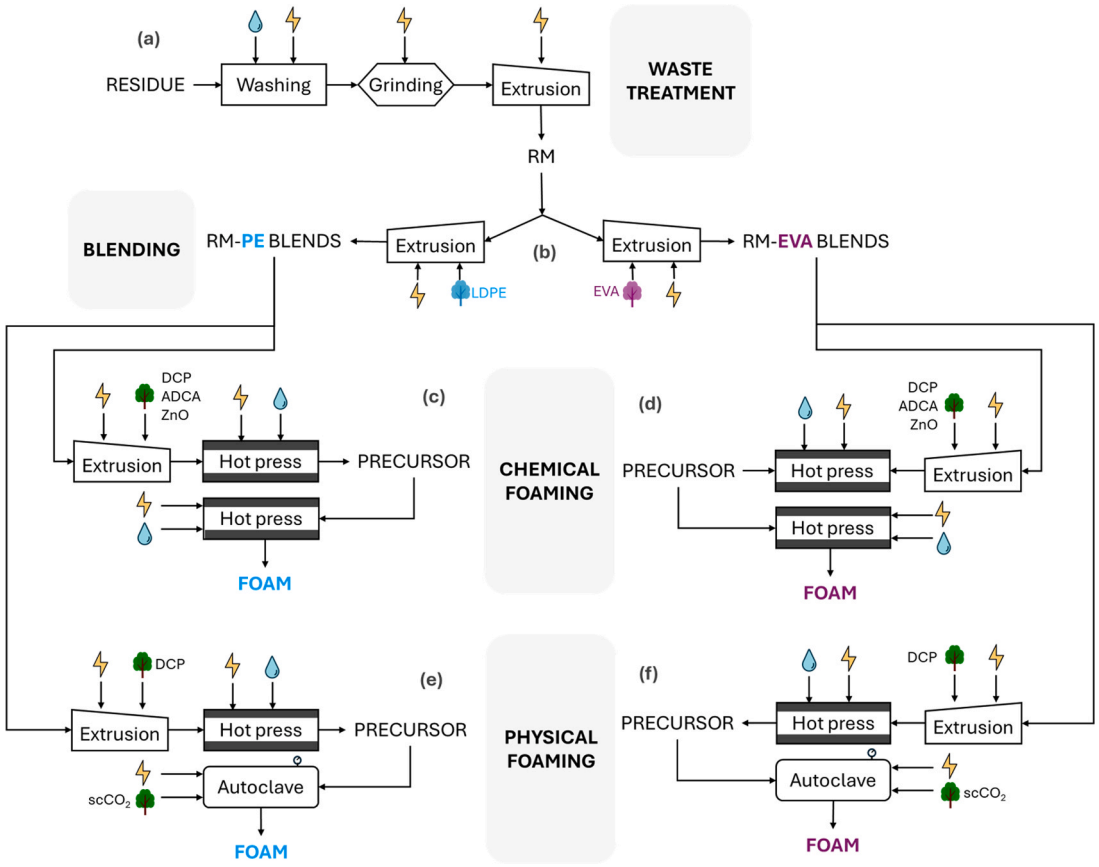


**Fig. 2.** Schematic representation of processes of (a) Waste treatment; (b) Blending; (c) Chemical foaming for PE blends; (d) Chemical foaming for EVA blends; (e) Physical foaming for PE blends and; (f) Physical foaming for EVA blends.

- Ph_RM:PE, 60:40(scenario 4)

These scenarios were chosen because they showed properties and performance comparable to the commercial product (scenario 0). The other foams produced were not included, as they did not meet the technical requirements for comparison and were therefore discarded. Assessing these technically successful cases through LCA made it possible to evaluate the viability of the products not only from a technical point of view but also from an environmental one, which is the main purpose of the LCA.

## 3. Results and discussion

The work consisted of the following two phases:

1. Manufacture of acoustic insulation foam from PE film waste. Firstly, various procedures, both for processing and foaming, were developed to transform RM into a technical foamed product with mechanical and acoustic properties comparable to a commercial product. For this purpose, different virgin polymers, RM ratios, crosslinking and two foaming techniques were considered. Then, the cellular structure and its functionality were characterized.
2. LCA of the developed system. Secondly, the environmental impact of the processes and products that met the technical requirements was assessed and compared to that of the commercial product. Since recycling and the use of recycled material involve additional processes, and incorporating recycled material changes the characteristics of the developed products, it does not inherently provide environmental benefits. Thus, conducting an LCA was found necessary in order to draw conclusions about its viability.

This section presents and discusses the main results of the two phases.

### 3.1. Manufacturing: RM blends, foaming, cellular structure study, and functionality characterization

#### 3.1.1. Study of RM and its blends

First of all, the rheology of RM and its blends was characterized. The material must exhibit appropriate melt behaviour to be processed, blended with other polymers, capable of incorporating foaming agents, uniformly dissolving a gas, and so on. In this regard, the mayor issues of RM were two: (1) high degree of heterogeneity leading to phase separation, and (2) high viscosity. This combination results, on the one hand, in a material that is difficult to be extruded, requiring severe conditions that inevitably lead to degradation of the less stable polymeric structures deteriorating its behaviour [22,24]. On the other hand, due to the high viscosity of the RM, there were limitations in incorporating foaming additives that resulted in poor dispersion and distribution, ultimately leading to a heterogeneous cellular structure. These issues were successfully addressed by blending with specific virgin polymers. The blending process focused on achieving a dominant phase to enhance compatibility among the different polymers present in the RM [41,42]. This was accomplished by adding a miscible polymer with LDPE fraction of RM and with a similar rheology (LDPE 410E or EVA 265 A). On the other hand, RM was blended with polymers able to compatibilize it in an extrusion process (Entira EP 1573 or EVA 265 A). Polymeric compatibilizers, combined with the shear applied by the twin-screw configuration, improve the distribution and dispersion of the dispersed phases. Effects of blending are discussed along this section.

Additionally, to generate a cellular structure, it is also necessary that the polymer exhibits a suitable response to extensional forces, so that it

can retain the gas and generating a homogeneous cellular structure. The fundamental requirement for a polymer to produce low-density good quality foams is to have a high melt strength. During the foaming process, the polymeric matrix is subjected to elongational forces. If the polymer is not able to withstand such stretching, the cell walls can break, promoting gas loss, coalescence and in general, degeneration of foam structure. Also, lower expansion degrees and therefore, higher densities than expected are obtained [43,44]. The resistance of a polymer when stretched can be measured by means of extensional tests through the determination of the strain hardening coefficient (SH) [43]. Various methods are known to confer or enhance this capability in polymers, with cross-linking of polymer chains being the most common approach, see Fig. 3(a, b). By linking the chains together to form a network, the ability of polymer chains to slide and flow under force is limited, resulting in the material opposing resistance to that force, increasing the resistance to deformation when subjected to loads, leading to a notable enhancement in the strain hardening coefficient. This is crucial for producing low-density technical foam, as the matrix must be able to retain the gas and avoid structural degeneration phenomena during expansion.

Fig. 3(c) shows the graph of the SH over time for the starting materials, i.e., RM, PE and EVA (see Supplementary information S4). It should be noted that, given the foaming processes were compression moulding and gas solution, the Hencky-strain rate selected was 1 $s^{-1}$, consistent with these techniques. Regarding results, in the figure it can be observed that while the non-crosslinked samples do not show an increase in elongational viscosity, the cross-linked ones do exhibit a rapid increase, also known as SH, at high deformations. This increase facilitates the formation and promotes the stabilization of the cellular structure. However, while cross-linking offers a technical advantage, it poses an environmental disadvantage, as interlinked polymer chains cannot melt due to these cross-linking bonds. Thus, the polymer cannot be reprocessed, making recycling more challenging and costly. In the study, both non-cross-linked and cross-linked cases were considered. However, we already anticipated that it would not be possible to obtain a foam comparable to the reference commercial product without cross-linking the matrix; the commercial product is cross-linked as well. Additionally, the results of the extensional rheology test also highlight the issues of phase separation and high viscosity already discussed. In the figure, it can be seen that the cross-linked RM specimen was breaking prematurely, as a consequence of its lack of integrity and rigidity. Thus, blending addresses issues of melt processing and foam generation.

### 3.1.2. *Foaming processes and optimization*

The different blends of RM, with PE or EVA, cross-linked and non-crosslinked, were foamed using two different foaming techniques. One was based on chemical foaming, and the other on physical foaming. Both procedures had to be adapted to the type of matrix.

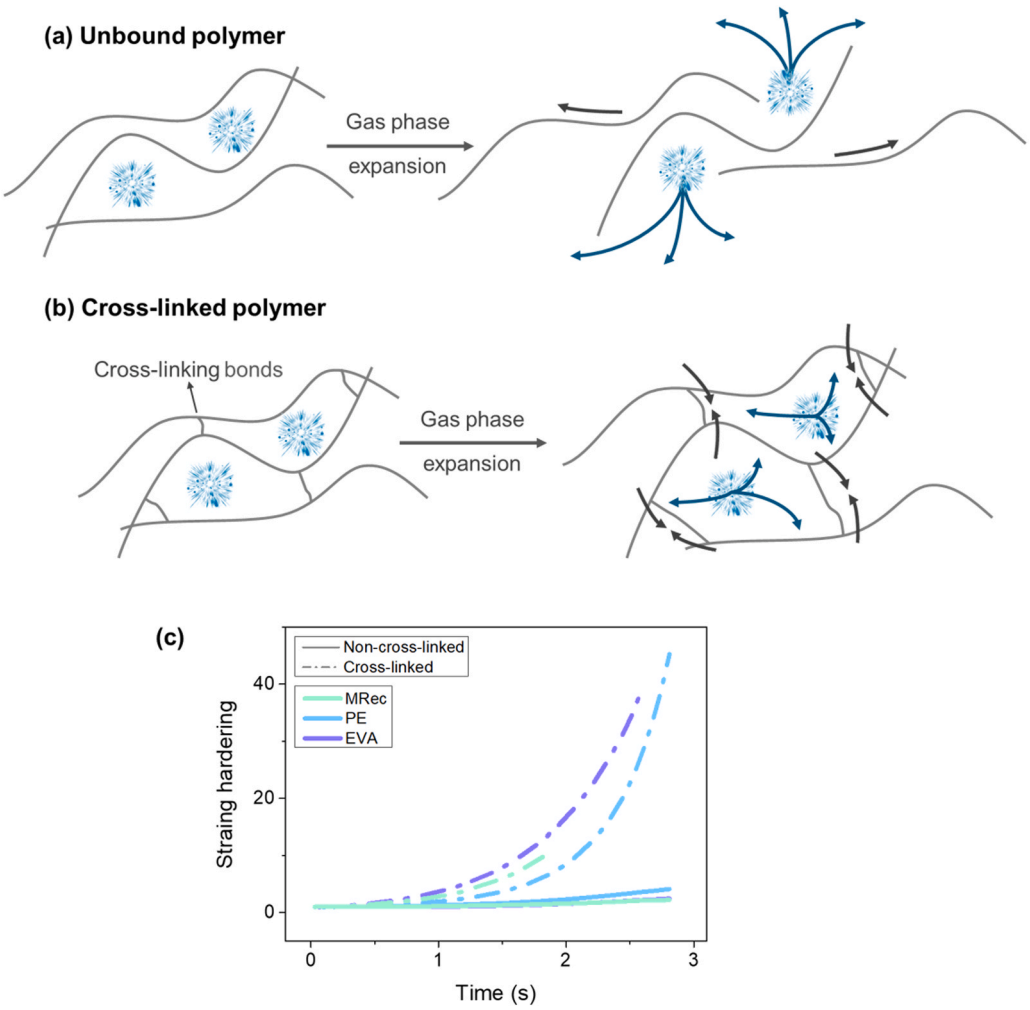


**Fig. 3.** Schematic representations of (a) the slide and flow of unbound chains due to the force of the gas during expansion, promoting gas loss, coalescence, and overall degeneration of the cellular structure, and (b) cross-linked chains, which allows the gas to be retained during expansion and stabilization of the structure. (c) Graph showing the extensional rheometry test results for the starting materials, with tests conducted at 1 $s^{-1}$ .

*3.1.2.1. Chemical foaming route.* Chemical foaming differs from physical foaming in the use of chemical blowing agents, which are compounds which must be incorporated into the polymer and typically decompose with increasing temperature, releasing a gas that forms the cellular structure. By this route, foams were obtained by the one-step compression moulding technique, which is widely described in the literature [45]. It is important to note that only the cross-linked matrices were able to form a cellular structure by this route. Given the forces during the expansion phase generated by the ADCA, the non-crosslinked matrices were unable to retain the gas, which simply created escape pathways in the matrix. This outcome was anticipated due to the strain hardening values. Therefore, only cross-link matrices were foamed by the chemical foaming route.

Cellular morphology of each trial was evaluated through SEM, and the degree of expansion was determined by measuring the foams density (see Supplementary information S5). Main conclusions are commented below.

i. In the foams based on PE, $T_f$ higher than 170 ºC cause a decrease of the expansion degree due to the lower matrix viscosity that allows gas to escape and a slight increase in cross-linking degree. Furthermore, for those blends containing EVA, optimal $T_f$ was 150 ºC. In this system, a lower temperature was needed to obtain the maximum expansion degree, because of the low melting temperature of this polymer (see Table 9).
ii. X-agent concentrations higher than 2 pph result in an excessive cross-linking degree, causing a decrease of expansion degree and the consequent increase in density. It must be pointed out that, although $T_f$ of RM-EVA blends were below X-agent (DCP) decomposition temperature (170 ºC), the optimum cross-linking degree of those samples was reached. The reason for this is that ADCA decomposes exothermically, generating the needed amount of energy for reaching the optimal cross-linking degree.
iii. On the other hand, for RM:PE blends the low ZnO concentration (2 pph) allowed obtaining foams with lower density and with more homogeneous cellular structures. However, for RM:EVA blends it was needed to use 10 pph, because of lower $T_f$ employed for those blends. Table 9 shows the optimal values for each system to produce good-quality foams.

*3.1.2.2. Physical foaming route.* Physical foaming was also considered. One-step gas dissolution technique was employed.

SEM was used to evaluate the cellular morphology and density tests were performed to determine the expansion degree of each trial (see Supplementary information S6). Table 10 shows the optimal conditions.

As observed previously in the chemical route and as expected, blends containing EVA needed lower $T_s$ than those of PE.

*3.1.3. Cellular structure study*

Once the process was optimized, all references were foamed according to the determined optimal conditions (see Table 9 and Table 10). These foams were characterized by SEM, see Fig. 4, and their density, average cell size and anisotropy was quantified, see Fig. 5. From SEM micrographs the average cell size and the average cell anisotropy were determined. Density of the precursors is provided in Supplementary Information S7.

**Table 9**
Optimal parameter values for chemical foaming.

| Parameter | Blend | |
|---|---|---|
| | RM:PE | RM:EVA |
| $T_f$ | 170 ºC | 150 ºC |
| X-agent | 2 pph | |
| ZnO | 5 pph | 10 pph |
| CBA | 15 pph | |
| $t_c$ | 90 s | |

**Table 10**
Optimal parameter values for physical foaming.

| Parameter | Blend | |
|---|---|---|
| | RM-PE | RM-EVA |
| $T_s$ | 140 ºC | 100 ºC |
| $P_s$ | 100 bar | |
| X-linking | Yes | |
| gas | $CO_2$ | |
| $t_s$ | 40 min | |

From the observation of the SEM images in Fig. 4, it can be quickly concluded that the chemical foaming process results in more homogeneous cellular structures with smaller cell sizes across the range of RM compositions compared to physical foaming. However, there are exceptions. A more detailed analysis is provided in Fig. 5.

Foams with lower density were obtained through chemical foaming compared to physical foaming, and using PE rather than EVA, although densities as low as the commercial product were not achieved, as can be seen in Fig. 5 [i] (a,b). Overall, chemical foaming is a more suitable as it results in lower density foams and is less sensitive to the composition of the blend and the content of recycled material. This latter aspect is particularly evident in the EVA samples, where chemical foaming exhibits markedly lower sensitivity to the mixture content compared to physical foaming. This phenomenon is due to the fact that ADCA, upon decomposition, not only releases gaseous compounds but also leaves a solid residue. This residue acts as a nucleating agent and has a strong effect as nucleating sites for the cells [46]. This leads to the formation of a more homogeneous cell structure with a smaller cell size and a higher cell density. On the other hand, the gas dissolution technique is more sensitive to the type of matrix since each polymer or polymer blend has a specific solubility for $CO_2$. Conversely, ADCA is distributed and dispersed in the material through extrusion. This does not imply that the chemical route is more homogeneous; rather, the sensitivity to the type of polymeric matrix is reduced because the extrusion conditions help mitigate this effect. As can be seen in Fig. 5 [i] (b), physical foaming conditions were more suitable for blends with a higher recycling content, resulting in much lower densities, which increase drastically with the content of virgin EVA.

With regards average cell size, Fig. 5 [ii] (a,b), the type of process (chemical or physical) is not as important as the composition. Overall, the samples from the chemical process are stable in both density and cell size. The variations observed when changing the composition are less pronounced than those in the physical process. This stability is attributed to the use of ADCA and the nucleating effect of its solid residue. Regarding the physical process, when examining PE, the density decreases as the content of virgin polymer increases. As a consequence, the cell size follows an opposite trend and increases. With lower density, the cell walls become thinner, promoting coalescence. Conversely, in the case of EVA, the density tends to increase while the cell size decreases.

Lastly, Fig. 5 [iii] (a,b) shows results of cell anisotropy measurements. Overall, chemical foaming results in foams with less anisotropy than physical foaming. This is because the samples in the chemical foaming process expanded within a mould, preventing the material from growing freely, which generally promotes greater anisotropies in cell size. However, physical foaming, can also achieve acceptable levels of anisotropy, but only at extreme compositions, Fig. 5 [iii] (b); at intermediate values, the anisotropy increases considerably, deviating significantly from isotropy (anisotropy $x/y = 1$) and the reference value. On the other hand, blend composition is only significant in chemical foaming, where PE is preferable over EVA, see Fig. 5 [iii] (a). Thus, to achieve quasi-isotropic cells (anisotropy $x/y \approx 1$), the combination of chemical foaming and PE is the most suitable across the entire range of compositions.

Therefore, chemical foaming allows to produce low-density foams

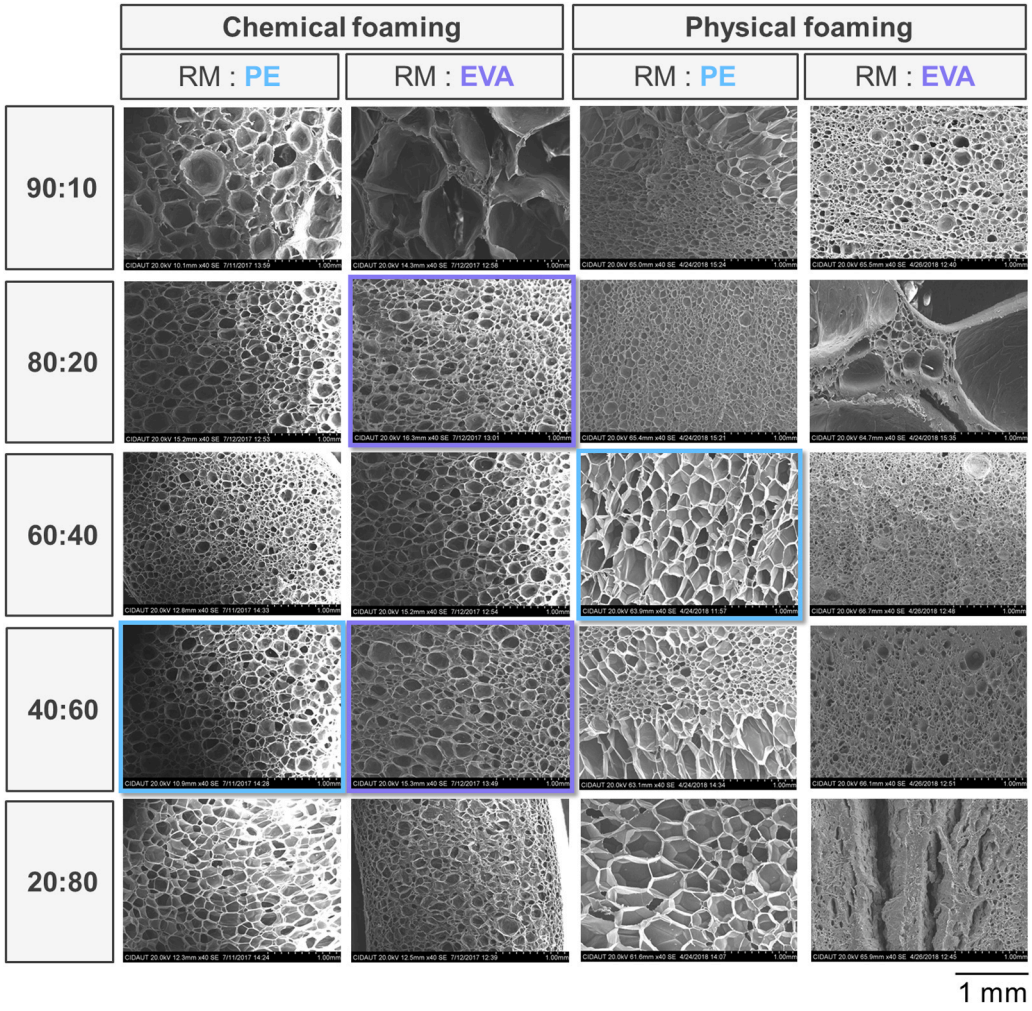


**Fig. 4.** SEM micrographs of the foams produced from RM.

with low sensitivity to the composition of the blend. Physical foaming also enables the production of foams with a density comparable to the commercial reference product but is more sensitive to blend composition. On the other hand, PE results in lower density foams, while EVA leads to smaller cell sizes without being significantly affected by the composition of the blend. In addition, the combination of chemical foaming and PE maintains quasi-isotropic cells across the range of compositions.

### *3.1.4. Functionality characterization*

Successful cases were characterized by the dynamic stiffness test. The criterion applied to select foams was that from each foaming technique (chemical and physical) and for each virgin polymer (PE and EVA), the foam with the lowest density was chosen, always below 100 kg/m$^3$ . This selection was made because higher density values resulted in significantly higher mass compared to the reference product, which implies substantially higher dynamic stiffness and environmental impact (to be discussed later) compared to the commercial reference. Additionally, the amount of recycled material needed to be equal to or greater than 40 wt% to ensure a substantial content of recycled material, and the values of average size and average anisotropy must be comparable to those of the reference. This resulted in three foams being selected: Ch_RM:PE,40:60, Ch_RM:EVA,40:60 and Phl_RM:PE,60:40, as is indicated in Fig. 5. Additionally, a foam with a high content of recycled material was considered, and Ch_RM:EVA,80:20 was chosen.

To connect the measured material properties with system-level acoustic performance in floating floors, the following considerations are pertinent. In floating-floor systems, dynamic stiffness per unit area is the key material property that governs the improvement in impact sound insulation at the system level. A lower dynamic stiffness per unit area shifts the fundamental resonance of the mass–spring assembly towards lower frequencies and increases the reduction of impact sound above that resonance for a given surface mass and top layer. This behaviour is consistent with laboratory evidence showing that decreases in dynamic stiffness per unit area are associated with better impact sound performance. However, dynamic stiffness per unit area is a single-number descriptor and does not, by itself, provide frequency-dependent information; frequency-resolved performance must be obtained from measurements on the complete floor system. This clarification frames how our results should be interpreted—linking material-scale measurements to system-level outcomes—and strengthens the practical relevance and transferability of the findings to design and assessment of floating-floor assemblies.

For the four selected samples, the dynamic stiffness was studied. Dynamic stiffness can be defined as the resistance of a material to deformation under oscillatory forces and is a crucial parameter in the characterization of materials when they are used for applications in acoustic insulation and vibration attenuation [38]. The acoustic insulation capacity of the material increases with decreasing dynamic stiffness, as the resonance frequency of the system decreases. This is because, at frequencies below resonance, the material behaves like a rigid solid, allowing all incident energy to pass through it. As a result, it does not have any damping effect in the event of an impact (e.g., stepping on the floor) and the energy can be transferred to other parts of the

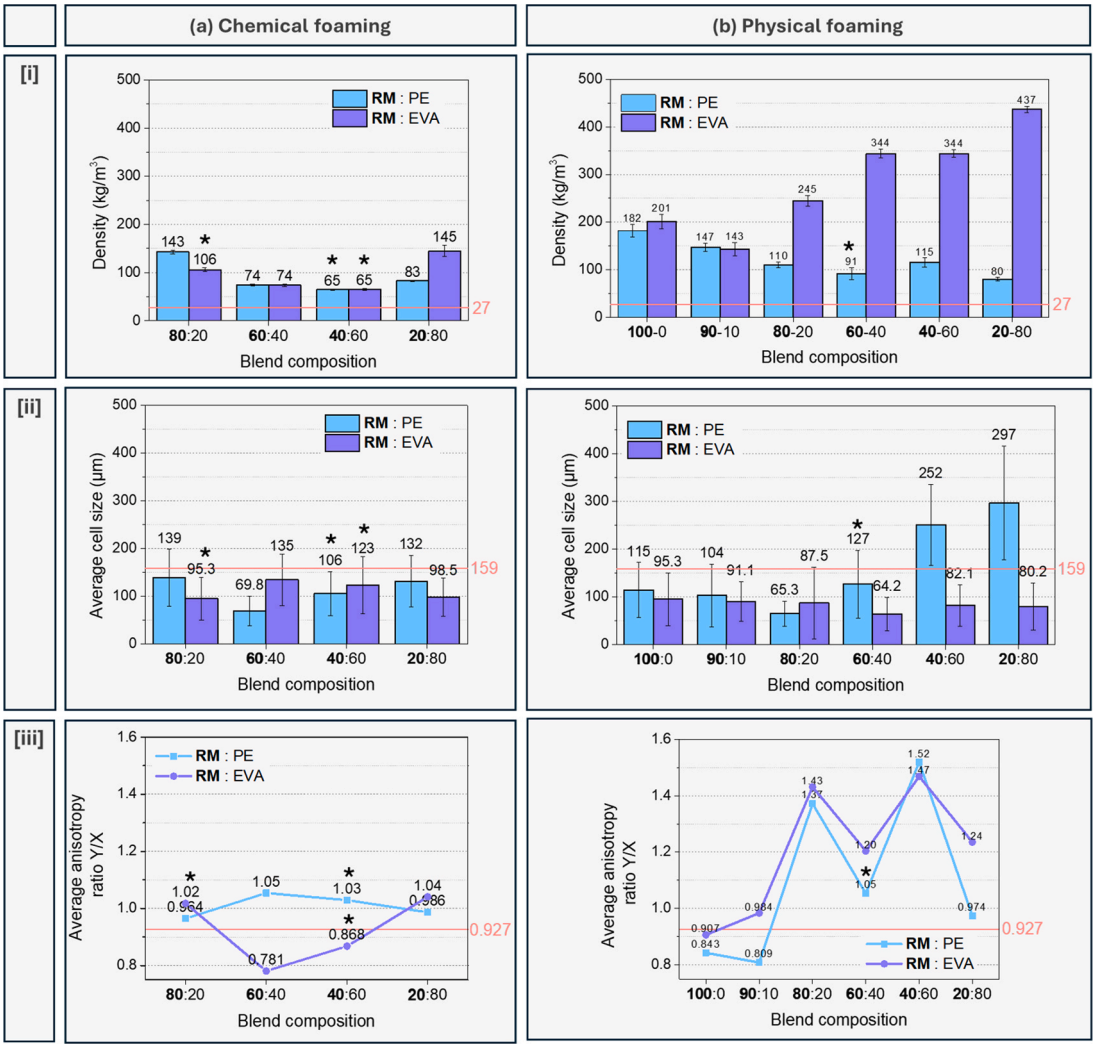


**Fig. 5.** [i] Densities, [ii] Average cell size and, [iii] Average anisotropy of foam obtained by (a) Chemical foaming and (b) Physical foaming. In each graph, the reference value corresponding to the commercial product has been indicated in red. The foams selected for the study are marked with an asterisk (*).

building structure, thus increasing noise, or causing vibrations. On the other hand, a material with high damping capacity may deform excessively under load, compromising its structural integrity. Therefore, a balance between damping and structural integrity is necessary. Dynamic stiffness takes into account these two parameters.

Relating the cellular structure of the developed foams to dynamic stiffness is complex. For a constant thickness, factors such as polymer type, foam density, and cell size, among others, influence dynamic stiffness. In these foams, all the mentioned factors vary. However, in general terms, for flooring insulation applications, particularly for polyethylene foams, low densities (below 100 kg/m³, preferably between 20 and 40 kg/m³) and relatively large cell sizes (100–4000 μm) are preferred [28,29,47–50]. The selected samples are within or close to these ranges, as can be seen in Fig. 6.

Fig. 6 also shows the dynamic stiffness values of the selected foam and the commercial reference product. Fig. 6 also reports the dynamic stiffness per unit area for the selected foams alongside the commercial reference. As can be observed, Ch_RM:EVA,80:20 and Ch_RM:EVA,40:60 reach values essentially equivalent to the reference, consistent with their combination of moderate bulk density and fine, relatively uniform cellular morphology, which together lower stiffness while preserving structural integrity. By contrast, Ch_RM:PE,40:60 exhibits a higher dynamic stiffness per unit area, attributable to its higher density, more developed surface skin, and cell anisotropy—features that confer greater

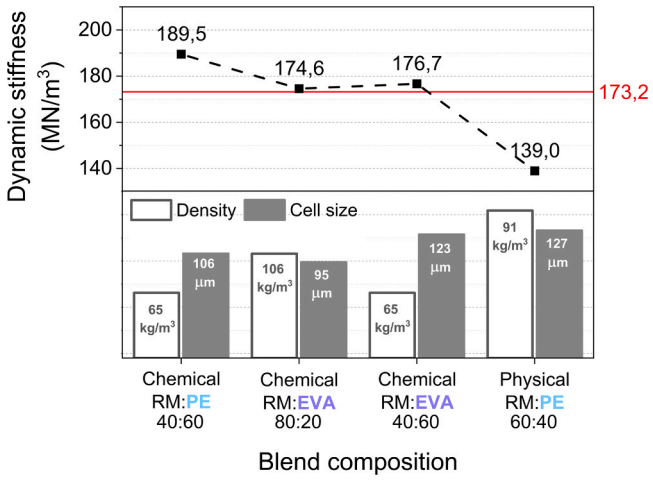


**Fig. 6.** Dynamic stiffness, density and cell size of the selected foams. The reference value for dynamic stiffness corresponding to the commercial product has been indicated in red. Dynamic stiffness values are given for a 140 kg/m² slab, as is the used in residential buildings.

integrity but reduce compliance under impact excitation. Conversely, Ph_RM:PE,60:40 presents a notably lower dynamic stiffness per unit area, in line with its lower density and coarser, less uniform cells characteristic of the physical foaming route; this combination increases compliance and thus the potential for reduced impact transmission, albeit with lower structural robustness. Taken together, these observations accord with the expected density–stiffness scaling of cellular solids and the modulating roles of cell size, anisotropy, and surface-skin effects, providing a coherent mechanistic explanation for the differences between the chemical and physical foaming routes. This represents an advance over previous studies on foams for building insulation applications, which incorporated 15–25 wt% of recycled PE into foams [28, 29], whereas in this work contents in the range of 40–80 wt% were successfully achieved while maintaining the required technical performance.

Therefore, from a technical point of view, the alternative to the commercial product is Ch_RM:PE,80:20, given its dynamic stiffness value and higher recycled material content. However, this decision only assesses the technical aspects of the final product and does not consider the process as a whole.

### 3.2. Life cycle assessment

The successful cases were achieved through different processes -chemical and physical foaming- and their composition -RM with PE or EVA- as well as characteristics -density and functionality- also varied. The impact of all these variables on the carbon footprint was measured using the LCA methodology.

First, a simplified LCA was conducted. The foams obtained have very different density values, implying much higher or lower mass quantities to be processed, depending on the case. This significantly increases or decreases the environmental impact simply due to the greater or lesser amount of material that needs to be processed. Thus, this first approach was to standardize the mass. Fig. 7 shows the results for the six impact categories selected: global warming potential, human toxicity, land use, fossil resource use, fossil water use, and primary energy demand. The graph shows the total contribution of each material per category.

The higher impact of the commercial product compared to the other scenarios clearly demonstrates the environmental profitability of utilizing recycled materials. Replacing virgin with recycled material involves new processes for waste conditioning, but it reduces the production processes of virgin material and the consumption of natural resources. This can be seen in more detail in the breakdown of contributions, see Fig. 8. Of the three stages, blending has the highest environmental impact. Due to the composition and rheological characteristics of RM, it cannot be used alone and needs to be mixed with virgin plastics. As seen in the graphs, this stage significantly increases the environmental impact, nearly doubling it. Therefore,

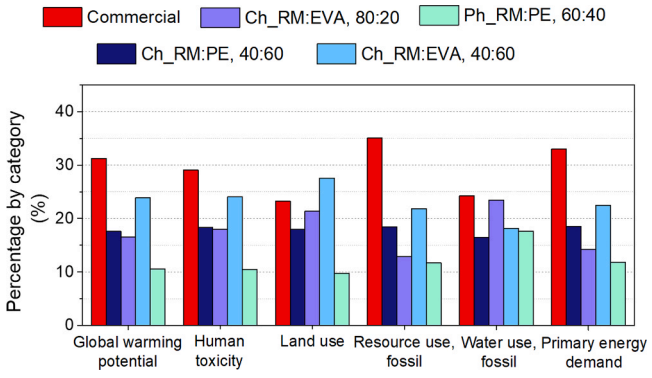


**Fig. 7.** LCA results for the functional unit of 1 kg of foam. The graph shows all the impact categories considered (6). For each indicator, the environmental impact is shown by material in percentage.

improving the characteristics of the waste, through enhanced sorting processes and/or eco-design, to avoid blending holds potential for substantially reducing environmental impact.

However, substituting virgin by recycled material is not as straightforward as claiming all positives; it has its strengths and weaknesses. In Fig. 7, a significant reduction in environmental impact indicators like resource use and primary energy demand can be observed. This is due to the aforementioned reduction in production processes for virgin material and the consumption of natural resources. Nevertheless, indicators like land use and water use show an increase with higher recycled content, primarily due to the washing stage of the residue. The model did not incorporate the treatment of wash water for reuse. Among all the considered processes for residue treatment, the washing stage proved to be the most demanding. While this stage was included but not studied in this research, the model suggests that optimizing the washing process could substantially improve the efficiency of residue recycling.

On the other hand, in Fig. 7 it is also clearly the lowest footprint of Ph_RM:PE,60:40 across all indicators. Given it has an intermediate RM content, this is attributed to the foaming technique. The gas dissolution technique showed a significantly lower footprint compared to the route with a chemical blowing agent. This result is consistent with the literature as it is known that gas dissolution technique has the advantage of a low environmental impact compared to other processes using compounds or solvents as blowing agents [51–53].

Comparing the breakdown of the materials obtained by the chemical route, see Fig. 8, it can be seen the benefits of a higher recycled content, comparing the blending stage of Ch_RM:EVA,80:20 vs Ch_RM:EVA,40:60, but also the differences in the foaming process depending on the virgin material. It can be seen that the process of foaming the PE blends has a lower carbon footprint than those containing EVA. The difference is that the former is more demanding in terms of temperatures, but the latter requires larger amounts of foaming agents. This is consistent with the conclusion in the previous paragraph, as the use of foaming compounds increases the carbon footprint given the processes involved in obtaining them versus higher energy consumption due to higher temperatures.

Therefore, a series of factors with significant influence on the footprint of the whole system were identified: the recycled content, the type of virgin polymer, and the foaming technique and procedure. However, only specific combinations of these factors resulted in foams comparable to the commercial reference product, and their properties were notably different. The following discussion addresses how the specifics of each scenario modify the environmental impact.

The first functional unit disregards the properties of the different foamed products, but the second functional unit takes these properties into account, incorporating empirical properties of each one. Fig. 9 and Fig. 10 show the total contribution for the six selected impact categories and the breakdown by stage, respectively.

According to Fig. 9, Ph_RM:PE,60:40 exhibited the highest environmental impact. This may seem contradictory to the fact that the physical foaming process has a lower carbon footprint than the chemical one. However, there are other factors to consider beyond just the foaming process itself. This material presents a series of technical disadvantages that contribute to this higher environmental impact. The causes lie in its combination of density and dynamic stiffness. Ph_RM:PE,60:40 has a higher density (91 kg/m$^3$) compared with the commercial product (25 kg/m$^3$) and also compared to Ch_RM:PE,40:60 (65 kg/m$^3$) and Ch_RM:EVA,40:60 (65 kg/m$^3$). A higher density results in a greater amount of material needed per unit area, thereby multiplying its impact. In LCA, an increase in quantities results in a significant rise in environmental impact, as it involves more resources and also leads an increase in energy demand. Thus, density of the foamed product is not only a key parameter in the technical aspects of achieving certain properties or behaviour, but also in the environmental aspects, having a significant influence on the footprint of the whole system. On the other hand, the dynamic stiffness of Ph_RM:PE,60:40 is also significantly

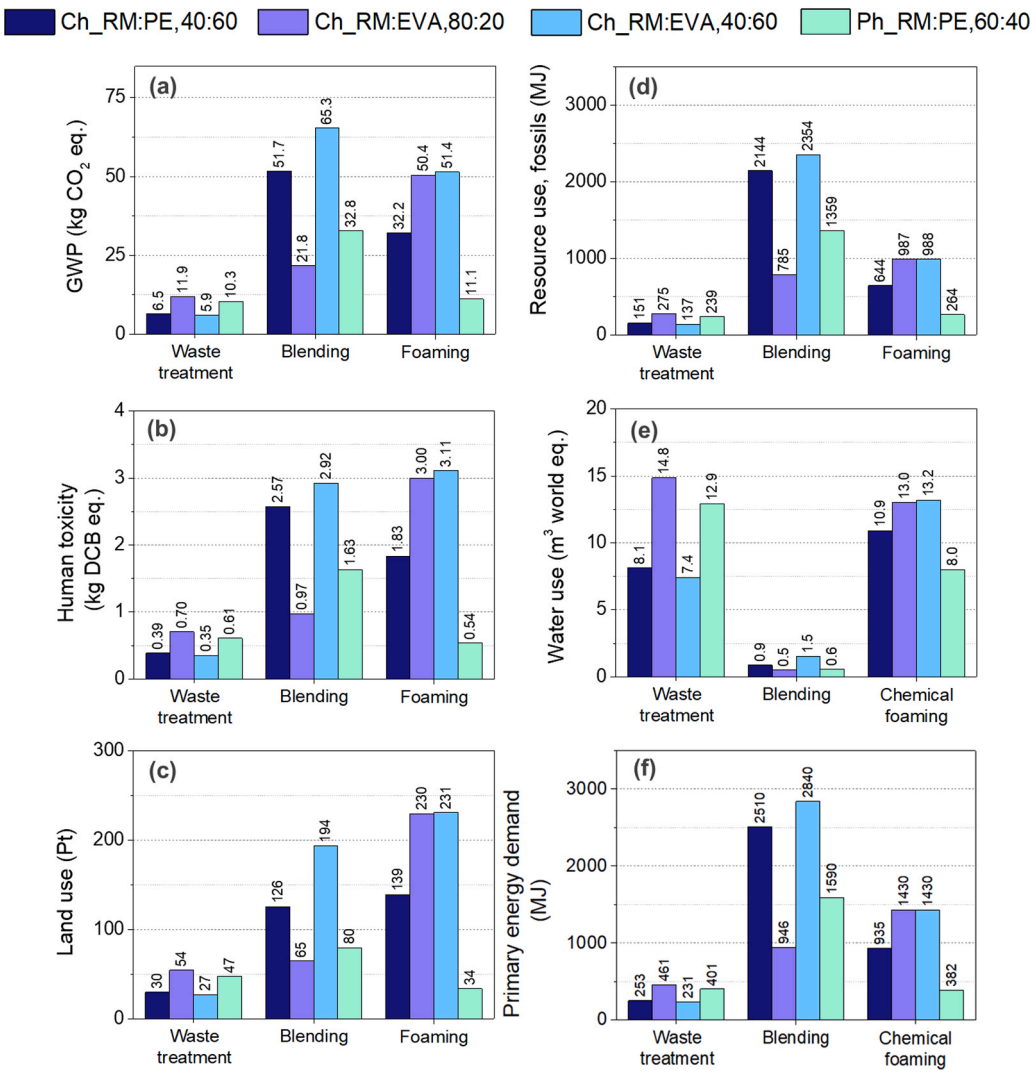


**Fig. 8.** Breakdown of the impact for the functional unit of 1 kg of foam for indicators: (a) Global warming potential, (b) Human toxicity, (c) Land use, (d) Resource use, fossil, (e) Water use, fossil, and (e) Primary energy demand.

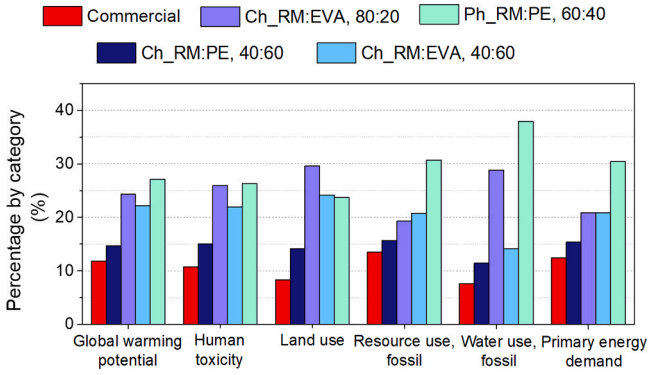


**Fig. 9.** LCA results for the functional unit of producing a foam with the required mass to achieve the dynamic stiffness of the commercial reference product. The graph shows all the impact categories considered (6). For each indicator, the environmental impact is shown by material in percentage.

different from the commercial product (139 vs 173.2 MN/m$^3$, respectively). Since it is lower, achieving the commercial value requires increasing the mass, according to Eq. 2:

$$s' = 4\pi^2 m' f_r^2 \quad (2)$$

in which $s'$ is the dynamic stiffness per unit area, $m'$ is the mass per unit area, and $f_r$ is the resonance frequency. The weight on the environmental impact of these mass increases can be seen in the breakdown of the total impact into its component processes in Fig. 10. In the graph, the light green bar corresponding to Ph_RM:PE,60:40 stands out in the waste treatment stage, despite having a lower recycled content than Ch_RM:EVA,80:20 (60 vs 80 wt%), and in the blending stage, despite having a lower content than Ch_RM:PE,40:60 and Ch_RM:EVA,40:60 (40 vs 60 wt %). Furthermore, in Fig. 10 shows that, despite the large amount of material, the physical foaming process has a low impact, indicating that the foaming process itself is not the cause of the high environmental impact. Therefore, the increases in mass above-described due to density and dynamic stiffness of Ph_RM:PE,60:40 have a significant impact on the overall footprint, making it the least suitable option despite the environmental advantage of the physical foaming process.

Ch_RM:EVA,80:20 also showed a high environmental impact, except for two categories; resource use and primary energy demand, see Fig. 9. This sample has the interesting characteristics of having a high recycled content and a dynamic stiffness value closest to the commercial reference. However, its environmental impact is notably high. This material has the highest density, 106 kg/m$^3$, which already knows that this

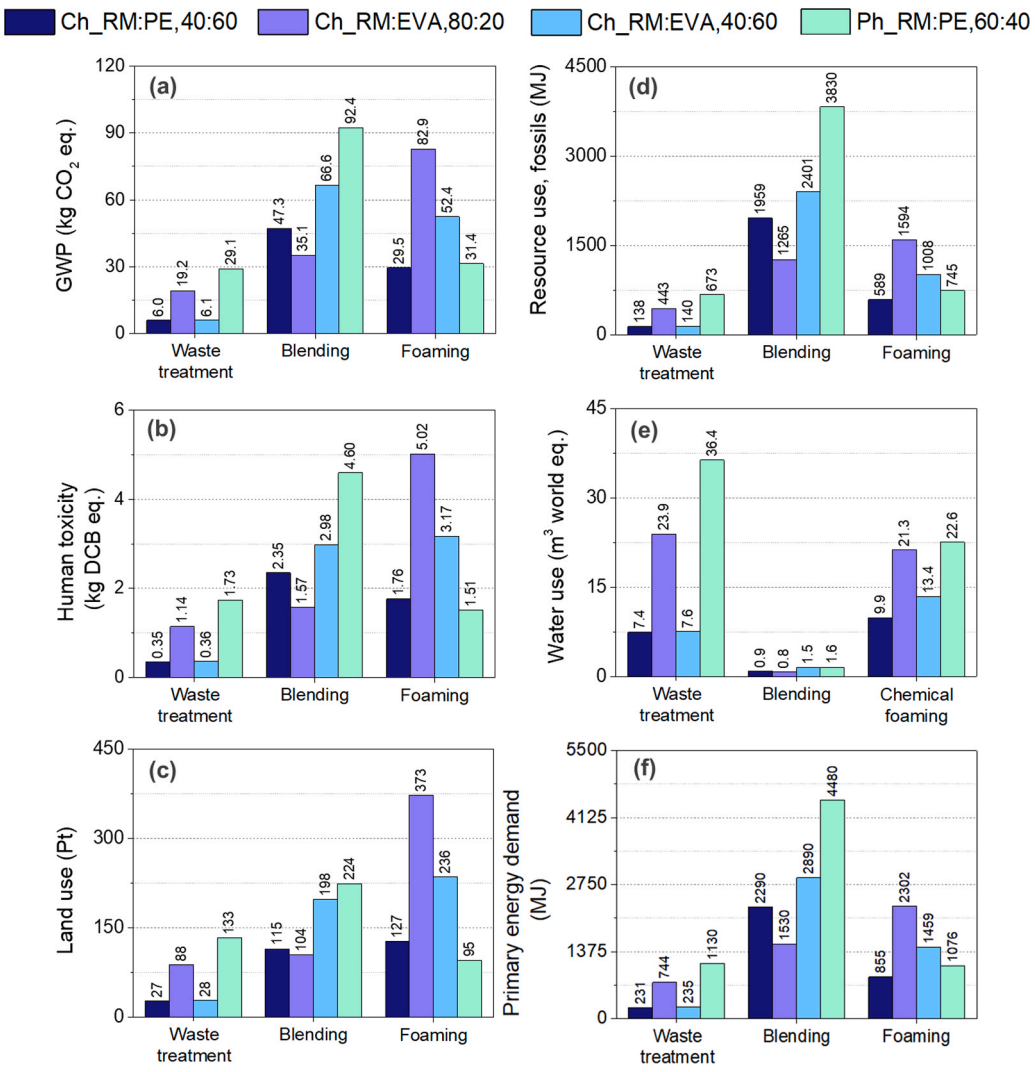


**Fig. 10.** Breakdown of the impact for the functional unit of producing a foam with the required mass to achieve the dynamic stiffness of the commercial reference product for indicators: (a) Global warming potential, (b) Human toxicity, (c) Land use, (d) Resource use, fossil, (e) Water use, fossil, and, (e) Primary energy demand.

increases the amount of material per unit area, significantly raising the whole system footprint. It is interesting to compare the impact of the foaming stage of this two samples: Ph_RM:PE,60:40 vs Ch_RM:EVA,80:20. According to LCI, the total mass for each of them was 183 kg and 105 kg, respectively. From Fig. 10 it can be seen t that despite the physically foamed sample having to process a higher mass, the foaming process itself had a significantly lower environmental impact. This leads to the conclusion that environmentally the physical foaming process, which relies on gas dissolution, is far less costly than the chemical process involving compression moulding. However, the fact of not having obtained a foam with properties close to the commercial one greatly penalises the physical route.

In contrast to Ph_RM:PE,60:40, Ch_RM:EVA,80:20 does not have as high an impact across all indicators. Its carbon footprint is notably reduced in terms of fossil resource use and primary energy demand, as can be seen in Fig. 9. Despite its high density, the high content of residual source material significantly reduces these two indicators. On the contrary, for Ch_RM:EVA,80:20 land use and water use stand out as being higher. The first is related to the chemical foaming process, and the second with the higher amount of waste material to be treated. In the breakdown of the impacts, Fig. 10, it can be observed that, across the different indicators, the waste treatment stage has the lowest environmental impact compared to blending and foaming, with a notable difference. However, the exception is water consumption, where the impact of waste treatment makes a significant contribution due to the washing process with a basic aqueous solution. For Ch_RM:EVA,80:20 the waste treatment stage is the highest, due to its combination of highest density and highest recycled content, resulting in a larger amount of residual material to be processed.

In the case of Ch_RM:PE,40:60 and Ch_RM:EVA,40:60, overall, the impact is reduced. It is interesting that both have the same density: 65 kg/m$^3$. This implies that the mass is almost the same, with a slight difference due to the small variation in dynamic stiffness. The RM content is also the same in both cases. Therefore, the only difference between them is the type of virgin polymer. The environmental impact of the waste treatment stage is practically the same for both, as seen in Fig. 10. However, since PE and EVA have different manufacturing processes, as defined in the GaBi professional database, and there were differences in the amounts of foaming agents and conditions for each, there are significant differences in the blending and foaming stages. In both stages, Ch_RM:EVA,40:60 shows a higher environmental impact. Since the amount of RM is the same, the higher impact in the blending stage is attributed to the highest impact of EVA obtaining from petroleum. This is interesting because the environmental impact was not considered in the criteria for selecting the virgin polymers. According to the results, it is an additional tool for significantly reducing environmental impact. On the other hand, the chemical foaming process was not exactly the same, see Table 9. The chemical foaming process for the PE

sample required higher temperatures, while the EVA sample required higher amounts of foaming agents. The results indicate that using more foaming agents has a higher environmental cost.

Therefore, Ch_RM:PE, 40:60 was the most environmentally favourable material. Although its carbon footprint was not lower than that of the commercial product, the differences were small: 3 % for GWP, 4 % for human toxicity, 6 % for land use, 2 % for resource use, 4 % for water use, and 3 % for primary energy demand. However, it is important to consider the lifetime of the recycled plastic to fully understand its impact. A waste from a short-lived packaging product (days) is being transformed into a long-lived construction product (years). The implications are as follows: The useful life of the plastic used in packaging applications is being extended and the problems associated with accumulating and treating packaging waste are being mitigated. Transitioning from a short-lived product to a long-lasting one results in a significant reduction in environmental impact, which was not fully accounted for in the LCA conducted.

## 4. Conclusions

This paper provides a comprehensive study from waste to the environmental implications of the recycled product. The research focused on manufacturing a recycled product with characteristics comparable to a commercial reference. Different contents of RM, various virgin polymers, cross-linking, and different foaming techniques -both chemical and physical- were studied. This resulted in four products meeting the technical requirements with different combinations of these factors. The environmental implications of each product were determined and analysed and areas for improvement were identified as well.

Two major problems were identified in the recycled material: a high degree of heterogeneity and high viscosity. These issues complicate processing and prevent the formation of a homogeneous cellular structure. To address these challenges, cross-linking and blending with virgin polymers were necessary. Cross-linking was essential to produce a low-density foam analogous to commercial products. Meanwhile, blending facilitated proper processing and the creation of homogeneous cellular structures. However, the LCA revealed that blending significantly increases the environmental impact, nearly doubling it. Therefore, reducing or eliminating the use of virgin polymers by improving the recycled material through enhanced sorting processes and/or eco-design has the potential to cut the carbon footprint by half.

Regarding the foaming processes, the physical foaming process showed a lower environmental impact compared to the chemical one. Despite this, the carbon footprint of the products obtained through the chemical process was lower. This is because the chemical route proved to be the most suitable for producing a low-density material with properties comparable to commercial products. The LCA was a highly useful tool, considering the system as a whole and enabling decisions beyond just the technical requirements of the product, guiding the selection of the most suitable options for within the framework of the circular economy.

In summary, foams with properties comparable to commercial products were achieved with a recycled material content ranging from 40 % to 80 % by weight. However, a balanced solution between technical and environmental considerations is necessary. Based on technical requirements, Ch_RM:EVA,80:20 is the optimal choice due to its dynamic stiffness value, which is almost equal to the commercial reference, and the recycled content, 80 wt%. In contrast, Ch_RM:PE,40:60 is more favourable from an environmental standpoint. The compromise solution that effectively addresses both technical performance and environmental impact is Ch_RM:EVA,40:60.

Finally, it should be noted that the LCA carried out only considers the production and use of the acoustic insulation product. However, it is important to consider that the plastic material is being transformed into a product with a long useful life. In addition to the obvious extension of the useful life, this transformation helps avoid the environmental impact and problems associated with accumulating waste and postpones the need for less environmentally favourable recycling processes, such as quaternary recycling.

## CRediT authorship contribution statement

**L.E. Alonso-Pastor:** Conceptualization, Methodology, Software, Validation, Formal análisis, Investigation, Data Curation, Writing - Original Draft, Visualization. **M.A. Morcillo:** Methodology, Validation, Formal análisis, Data Curation, Writing - Review & Editing. **E. Laguna-Gutiérrez:** Methodology, Validation, Formal análisis, Data Curation, Writing - Review & Editing. **P. Baños:** Resources, Writing - Review & Editing. **J. García:** Resources, Writing - Review & Editing. **J.L. Moreno:** Resources, Writing - Review & Editing. **M.A. Rodríguez-Pérez:** Conceptualization, Visualization, Project administration, Funding acquisition. **K.C. Nuñez Carrero:** Conceptualization, Validation, Investigation, Writing - Review & Editing, Visualization, Supervision, Project administration, Funding acquisition.

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## Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Karina Carla Nunez Carrero reports financial support was provided by Ministerio de Economía y Competitividad. Miguel Angel Rodriguez Perez reports financial support was provided by Next Generation EU and Castilla y Leon funds. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.conbuildmat.2025.144309.

## Data availability

No data was used for the research described in the article.

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