

Deliverable D4.3

Report on plastic materials recycling and performance validation at pilot scale



Feasible Recovery of critical raw materials through a new circular Ecosystem for a Li-Ion Battery cross-value chain in Europe

WP 4 - Scaling and validation of feasible technologies

D4.3 - Report on plastic materials recycling and performance validation at pilot scale

Due date of deliverable
31/05/2026

Actual submission date:
29/05/2026

Organisation name responsible for this deliverable:
AIMPLAS

Dissemination Level

SEN	Sensitive	
PU	Public	X

Project Acronym
FREE4LiB

Project Start Date
01-09-2022

Duration
48 months

Grant Agreement No.
101069890

Project End Date
31-08-2026



Funded by
the European Union

Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them. This project has received funding from Horizon Europe research and innovation programme under Grant Agreement No.1069890

@FREE4LiB
 FREE4LiB
 freeforlib.eu

Disclaimer

©2022 FREE4LIB Consortium Partners. All rights reserved.

Free4lib is an EU-funded project that has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no. 101069890. The sole responsibility for the content of this report lies with the authors. It does not necessarily reflect the opinion of the European Union. The European Commission is not responsible for any use that may be made of the information contained therein.

While this publication has been prepared by the consortium partners of the project, the authors provide no warranty with regards to the content and shall not be liable for any direct, incidental or consequential damages that may result from the use of the information, or the data contained therein.

Versions

DATE	VERSION	AUTHOR	COMMENT
21/01/2026	1	AIMPLAS	First draft of the document
07/05/2026	2	FRAUNHOFER	First review
18/05/2026	3	AIMPLAS	Final document



Contents

1. Executive summary.....	7
2. Introduction.....	7
3. Scale-up for plastics recycling	8
3.1. Decontamination of recovered thermoplastics by SC- CO ₂	8
3.1.1. Experimental approach.	9
3.2. Upcycling of thermoplastic compounds for reuse in new applications.....	18
3.2.1. Case study #1 Cell pouch frames.....	19
3.2.2. Case study #2 Pipes and tubes cooling system	25
3.2.3. Case study #3 Protective and insulating panels.....	29
4. Conclusions	36

List of Abbreviations

ACRONYMS	DESCRIPTION
ABS	Polyacrylonitrile-Butadiene-Styrene
EoL	End of Life
EV	Electric Vehicle
FTIR	Fourier Transform Infrared spectroscopy
HDPE	High Density Polyethylene
NIR	Near-infrared
PA	Polyamide
PC	Polycarbonate
PPE	Polyphenylene ether
PP	Polypropylene

List of figures

Figure 1. Cooling tubing from battery packs.	9
Figure 2. SC-CO ₂ assisted extrusion line	10
Figure 3. Input and output of contaminated PA11 tubing, from left to right .	11
Figure 4. Decontamination, stability limit on SC-CO ₂ injection.....	12
Figure 5. Blank sample VOCs GC-MC results.....	15
Figure 6. PCR tubing sample baseline VOCs GC-MC results.....	16
Figure 7. PCR tubing sample application-related VOCs GC-MC results.....	17
Figure 8. Cell pouch frames from battery packs.....	19
Figure 9. Double screw extruder pilot scale.	20
Figure 10. Upcycled PPE pellets made of 25%, 50% and 75% recycled content from left to right.	20
Figure 11. Injection mould design and assembly.....	23
Figure 12. Injection-moulded demonstration frame (50% rPPE compound) – validation of upcycled PPE formulation for circular application in EV battery systems.	23
Figure 13. Filament 1,75 mm for 3D printing, made of 50% PCR PPE.....	24
Figure 14. Upcycling workflow PA11 cooling tubes.	25

Figure 15.Upcycling process of decontaminated PA11pellets via extrusion compounding.	26
Figure 16. Piping extrusion line.	28
Figure 17.EPP insulating panels from battery packs.	30
Figure 18. Tandem extrusion foaming system.	30
Figure 19.Foaming extrusion die.	31
Figure 20. Average foaming profile for each sample.	32
Figure 21. Microscopy images of foamed samples containing 10%, 20%, and 30% rPP showing evolution of pore structure and cell morphology.	35

List of tables

Table 1.Decontamination melt extrusion process – Process stability	11
Table 2. Decontamination melt extrusion process - Outputs	11
Table 3. Melt Flow Rate (MFR) (g/10min) for decontaminated samples.	13
Table 4. Mechanical characterization of decontaminated PCR Hyundai tubing samples	14
Table 5.Decontamination efficiencies for the removal of baseline VOCs fraction.	16
Table 6. Decontamination efficiencies for the removal of application-related VOCs fraction.	17
Table 7. Upcycled PPE material properties characterization.	21
Table 8. Upcycled materials obtained via extrusion compounding.	26
Table 9. Mechanical characterization of decontaminated PCR Hyundai tubing samples	26
Table 10. Tubing validation of upcycled PA for circular application in EV battery systems.	29
Table 11. Physical analysis characterization	32
Table 12. Bulk density characterization results.	33

1. Executive summary

The present report details the research and development activities carried out within Task 4.5 – *Scale-up for plastic materials recycling*, aimed at the valorisation of thermoplastics recovered from end-of-life (EoL) EV battery packs. Building upon the methodologies and preliminary findings established in WP3, this task focuses on the pilot-scale implementation (TRL 5–6) of advanced processes for the recycling, decontamination, and upcycling of engineering thermoplastics previously identified and characterised in Task 3.5.

The scope of the work encompasses the following main activities:

- Decontamination of recovered polymers through supercritical CO₂ (SC-CO₂) melt filtration at pilot scale to remove volatile organic compounds (VOCs), typically responsible for quality degradation and downcycling.
- Reprocessing and upcycling of thermoplastics via compounding and extrusion to obtain high-value materials suitable for technical and structural applications.
- Validation of mechanical and processing performance of recycled compounds, confirming feasibility at incorporation levels up to 50–70% recycled content.

The results obtained under *Task 4.5* provide a robust technical foundation for the validation of these recycling and upcycling technologies at pilot scale, demonstrating their technical, economic, and environmental viability. In addition, selected recovered plastics will be supplied to AVL to produce a demonstrator battery, showcasing the integration of recycled materials in new battery systems.

2. Introduction

Plastics have become a cornerstone in modern mobility systems due to their exceptional combination of lightweight design, mechanical robustness, chemical resistance, and flexible processability. In electric vehicles (EVs), polymers such as PP, PA, PPE, and EPP are widely used in battery housings, cooling circuits, insulation panels, connectors, and enclosures—serving not only to reduce weight but also to integrate thermal, structural, and protective functions.

However, polymers recovered at end of life (EoL) often exhibit degradation: thermal cycles, mechanical stresses, oxidation, additive leaching, and polymer chain scission degrade molecular integrity, causing reductions in strength, stiffness, ductility, and thermal stability. Mechanical recycling alone cannot compensate these losses, leading to downgrading of material applications.



Upcycling strategies instead aim to restore and enhance performance by coupling purified recyclates with compatibilizers, reinforcements, reactive additives or fillers, thereby minimizing the gap with virgin material performance (a strategy often called functional upcycling¹)

In parallel, the regulatory landscape in Europe is evolving toward mandatory incorporation of recycled plastics in automotive components. Under proposed revisions to the End-of-Life Vehicles (ELV) regulation, new vehicles may be required to include 15–25% recycled plastic content in future production^{2,3}. This legislative momentum underscores the urgent need for scalable and validated recycling/upcycling technologies in the EV sector.

Within that framework, FREE4LIB has not only recovered and decontaminated battery-derived plastics, but also systematically characterised their mechanical, thermal, and processing properties and benchmarked them against commercial polymer grades. These comparisons have revealed precise degradation gaps and permitted the identification of targeted strategies to elevate recyclates performance. Accordingly, Task 4.5 is structured around two synergistic pathways: (i) *decontamination via SC-CO₂ melt filtration, aimed at removing residual volatiles and recovering polymer purity*; and (ii) *upcycling via compounding and extrusion*, designed to restore or enhance mechanical, thermal, and rheological properties of the recycled polymers to levels competitive with virgin materials.

3. Scale-up for plastics recycling

3.1. Decontamination of recovered thermoplastics by SC- CO₂

From the components recovered from dismantled battery packs supplied by different partners (ACC, EURECAT, and WATT4EVER), along with additional plastic parts provided by CARTIF and FRAUNHOFER, AIMPLAS identified and selected the most suitable polymers for decontamination and upcycling, based on their intrinsic properties, processing potential, and market value.

¹ Guselnikova, O., Semyonov, O., Sviridova, E., Gulyaev, R., Gorbunova, A., Kogolev, D., Trelin, A., Yamauchi, Y., Boukherroub, R., & Postnikov, P. (2023). Functional upcycling of polymer waste towards the design of new materials. *Chemical Society Reviews*, 52(14), 4755–4832. <https://doi.org/10.1039/D2CS00689H>

² European Parliament. (2025, July 7). Circular economy: New EU rules to make the automotive sector more sustainable [Press release]. <https://www.europarl.europa.eu/news/en/press-room/20250707IPR29462/circular-economy-new-eu-rules-to-make-the-automotive-sector-more-sustainable>

³ European Commission. (2023, July 13). Proposal for a regulation of the European Parliament and of the Council on circularity requirements for vehicle design and on management of end-of-life vehicles, amending Regulations (EU) 2018/858 and 2019/1020 and repealing Directives 2000/53/EC and 2005/64/EC (COM (2023) 451 final). <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023PC0451>



Among the recovered items, particular attention was given to cooling system components (*Figure 1*), which comprise an assembly of pipes and tubes designed to circulate cooling fluids throughout the battery system. These parts are typically exposed to heat transfer fluids that may contain toxic additives or contaminants, potentially limiting their direct reintegration into new applications without prior treatment.

Within these assemblies, several polymer types were identified—primarily polyamide-based materials such as PA66 and PA11. However, certain fittings and injection-moulded parts made of PA66 were excluded from further processing due to their incompatibility with melt extrusion techniques used in the selected decontamination process. Consequently, only extruded tubing manufactured from PA11 was selected for pilot-scale CO₂-assisted melt filtration (SC-CO₂ stripping), aimed at achieving efficient removal of volatile contaminants and obtaining high-purity recyclates suitable for subsequent upcycling operations.

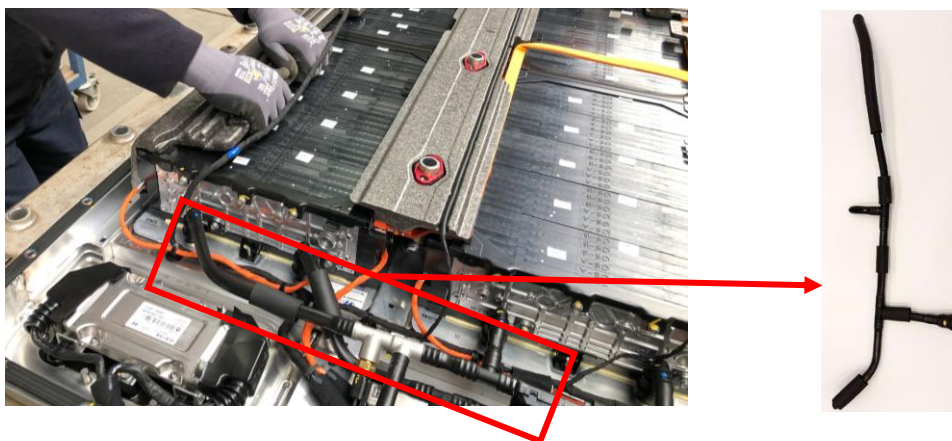


Figure 1. Cooling tubing from battery packs.

3.1.1. Experimental approach.

Regarding the process, decontamination using supercritical CO₂ (SC-CO₂) was carried out through a stripping extrusion step in a single-screw extruder equipped with a degassing zone and a dedicated stripping section (*Figure 2*). During processing, SC-CO₂ was injected into the molten polymer, where it acted as a physical solvent and stripping medium. Above its critical point (31,1 °C and 73,8 bar), CO₂ acquires a dense fluid phase with gas-like diffusivity and liquid-like solvating power, allowing it to penetrate the polymer matrix and efficiently dissolve and extract volatile organic compounds (VOCs) and low-molecular-weight contaminants. When pressure is released at the extruder vent, CO₂ rapidly expands and outgasses, carrying away the extracted volatiles without leaving solvent residues.

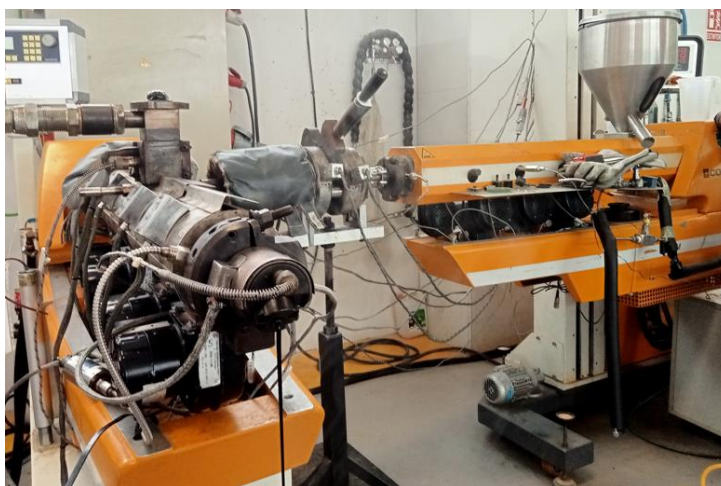


Figure 2. SC-CO₂ assisted extrusion line

This approach was selected due to its proven high efficiency in the removal of absorbed or embedded contaminants from post-consumer polymers, while maintaining the structural integrity and mechanical performance of the material. Previous studies ^{4,5} have shown that SC-CO₂ treatment can eliminate up to 90–100% of low-molecular-weight volatiles from recycled polyolefins and polyamides, as CO₂ diffusion and polymer swelling facilitate contaminant desorption and mass transfer. Moreover, the use of supercritical CO₂ (SC-CO₂) offers several advantages compared to conventional chemical solvents, including low flammability, chemical inertness, and non-toxic, non-corrosive behaviour. The process can be considered environmentally benign and fully recyclable, as CO₂ can be potentially recovered and reused in a closed-loop system, thereby avoiding the generation of liquid effluents or hazardous residues.

The feedstock for the extrusion process consisted of pre-shredded cooling tubes, reduced to flakes of approximately 3–5 mm to ensure continuous and stable feeding throughout processing. The process output was a uniform stream of decontaminated polymer pellets, subsequently intended for mechanical and physical testing as well as for VOCs content analysis. Figure 3 illustrates the corresponding input material and resulting output pellets, respectively.

⁴ Ben Said, S., Morin, C., Peydecastaing, J., & Vaca-Garcia, C. (2016). Supercritical CO₂ extraction of contaminants from polypropylene. *The Journal of Supercritical Fluids*, 118, 17–25. <https://doi.org/10.1016/j.supflu.2016.07.015>

⁵ Preetam, A., Kurian, A., & Bhattacharya, S. (2023). Supercritical fluid technology: An eco-friendly approach for resource recovery and waste valorization. *Separation and Purification Technology*, 316, 123819. <https://doi.org/10.1016/j.seppur.2023.123819>

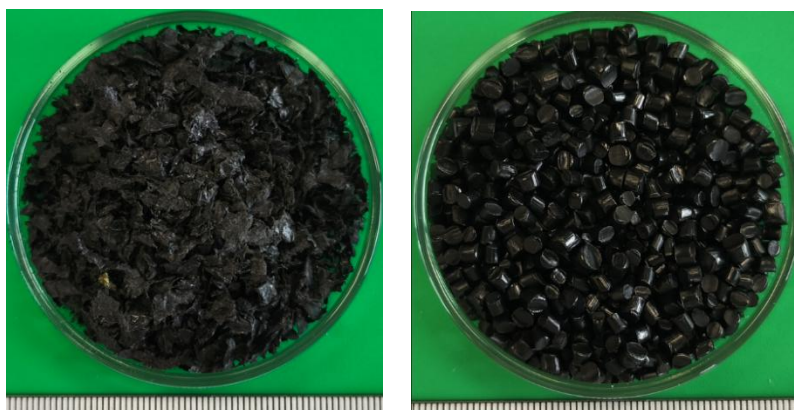


Figure 3. Input and output of contaminated PA11 tubing, from left to right

During the process, in addition to the recovered flakes, an industrial-grade reference material with comparable performance and application was processed as a control sample to monitor process stability and establish a performance benchmark. Since reprocessing can generate secondary volatiles, the comparison between the control and the recycled samples also enables an accurate evaluation of stripping efficiency and the identification of residual volatile compounds. The commercial reference grade used for this purpose was RILSAN® BESN BLACK P210 TL.

The process outputs obtained for the decontamination study are represented in Table 1 and Table 2:

Table 1. Decontamination melt extrusion process – Process stability

Sample	CO ₂ /polymer ratio% (wt./wt.)	Production (g/h)	CO ₂ Injection pressure	Process stability (Y/N)
Blank sample	0	5.244	0	Y
	5		121,7	Y
	10		163,2	Y
	15		187,9	N
PCR tubing HYUNDAI	0	5.244	0	Y
	5		155	Y
	10		207	N

In all cases, the supercritical conditions (31.1 °C and 73.8 bar) could be achieved; nonetheless, for CO₂/polymer ratios greater than 5% in the recovered Hyundai tubing, the process became unstable, marking this as the limit. This is possibly due to the melt viscosity of the material.

Table 2. Decontamination melt extrusion process - Outputs

Sample	CO ₂ /polymer ratio% (wt./wt.)	Melt temperature (°C)	Melt pressure extruder 1 (bar)	Melt pressure extruder 2 (bar)
Blank sample	0	200	77	47
	5	200	81	42
	10	201	76	43

	15	201	80	48
PCR tubing HYUNDAI	0	200	73	46
	5	201	75	46
	10	200	72	44

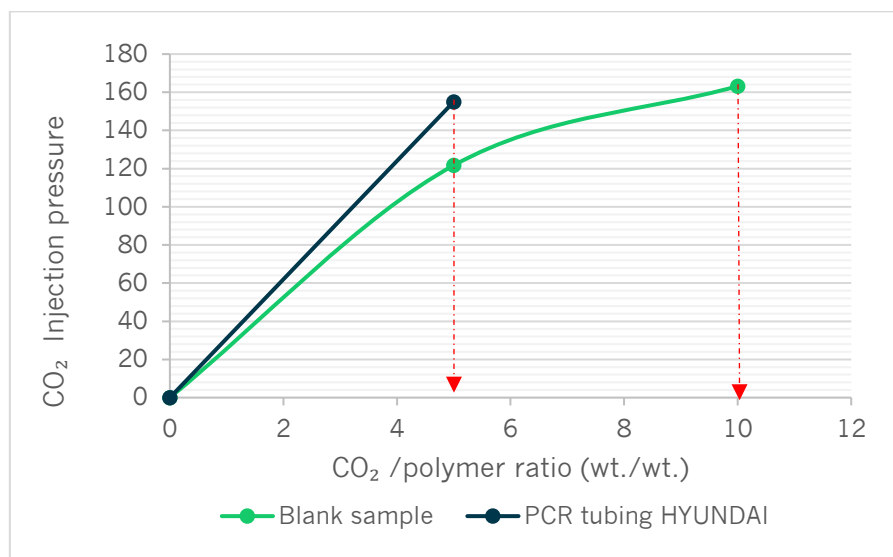


Figure 4. Decontamination, stability limit on SC-CO₂ injection.

The processing outputs obtained during SC-CO₂-assisted extrusion provides key insights into the operational limits of the decontamination process, particularly in relation to the maximum CO₂/polymer ratio that can be introduced while maintaining melt stability (Figure 4).

For the industrial-grade reference material (Rilsan ® BESN P210 TL), stable extrusion behaviour was maintained up to a 10% CO₂/polymer ratio (wt./wt.). Across this range, the process exhibited continuous feeding, stable melt pressure and temperature, and no venting anomalies. Instability appeared only at 15% CO₂, where excessive CO₂ uptake into the melt resulted in a marked reduction in viscosity, affecting the screw's conveying efficiency (see Table 1).

In contrast, the recovered Hyundai PA11 tubing showed a significantly lower tolerance to SC-CO₂ injection. Processing remained stable at 5% CO₂, but clear instability occurred at 10%, indicating a narrower processing window. This behaviour suggests that the recycled PA11 is more susceptible to CO₂-induced rheological changes, likely due to variations in molecular weight distribution, polymer chain integrity, absorbed contaminants, and morphological heterogeneity. Regarding the rheological changes observed, when introduced under supercritical conditions, CO₂ dissolves into the molten polymer and behaves as a transient plasticizer. This interaction increases the mobility of polymer chains and leads to a temporary reduction in melt viscosity while the CO₂ remains

dissolved in the polymer matrix. Once pressure is released in the degassing zone, the CO₂ rapidly desorbs, and the melt viscosity returns to normal.

However, when the CO₂ content becomes excessively high, CO₂ bubbles may form within the molten polymer, stripping entrained volatile compounds. This transient plasticisation can lead to insufficient melt pressure build-up, instability in the degassing section, and an overall loss of process stability.

This explains why the recovered PA11 becomes unstable at 10% CO₂, whereas the virgin reference grade exhibits a wider tolerance. The melt viscosity of the samples was analysed in order to identify relevant changes in melt viscosity that could refer to the decontamination process anomalies described above. The results obtained can be seen in Table 3:

Table 3. Melt Flow Rate (MFR) (g/10min) for decontaminated samples.

Sample	MFR (g/10min)	MVR (cm ³ /10min)	Comments
Rilsan BESN black P210TL 0% CO ₂	4,77 ± 0,26	-	
Rilsan BESN black P210TL 5% CO ₂	4,97 ± 0,2	-	
Rilsan BESN black P210TL 10% CO ₂	4,84 ± 0.26	-	
Tubes HYUNDAI PCR	-	4,06 ± 4,06	High morphological heterogeneity.
Tubes HYUNDAI 0% CO ₂	2,01 ± 0,09	-	
Tubes HYUNDAI 5% CO ₂	0,44 ± 0,02	-	

The virgin reference polymer maintains stable rheological behaviour and processability up to 10% CO₂, indicating that the supercritical treatment does not induce structural degradation. In contrast, the recovered PA11 shows a significantly narrower processing window, with process instability and strong MFR reductions appearing above 5% CO₂, consistent with its higher sensitivity to CO₂-induced transient plasticization. Regarding mechanical performance, the decontaminated samples were analysed and benchmarked against the reference material (RILSAN® BLACK P210) to assess potential changes attributable to the decontamination process and to support the definition of subsequent upcycling strategies. The corresponding results are presented in Table 4:

Table 4. Mechanical characterization of decontaminated PCR Hyundai tubing samples

Property	Test method	Unit	Rilsan Black P210	PCR HYUN-DAI tubing	PCR HYUN-DAI tubing 0% CO ₂	PCR HYUN-DAI tubing 5% CO ₂
Tensile Modulus	UNE-EN ISO 527-2	MPa	600	485±120	440±76	518±48
Yield Stress	UNE-EN ISO 527-2	MPa	32	27,1±0,6	28,4±0,6	26,7±1
Yield Strain	UNE-EN ISO 527-2	%	31	22±3	35±4	37±1
Nominal strain at break	UNE-EN ISO 527-2	%	>50	29±4	170±10	180±20
Charpy impact resistance Notch @ 23°C	UNE-EN ISO 179/1eA	kJ/m ²	76	47,6±3	74,6±8	86,7±5
Charpy impact resistance notch @ -30°C	UNE-EN ISO 179/1eU	kJ/m ²	10	5,7±1	8,4±1	11,9±0,9

Mechanical characterisation shows that SC-CO₂-treated samples maintain key properties such as ductility and impact resistance when compared to untreated reference material. These results support the suitability of the decontaminated PA11 for further upcycling strategies without compromising mechanical performance.

To quantify the effectiveness of the SC-CO₂ decontamination treatment, the total content of volatile organic compounds (VOCs) was evaluated before and after extrusion using gas chromatography coupled with mass spectrometry (GC-MS). The objective of the VOCs strategy was twofold: (1) to distinguish VOCs related to intrinsic PA11 composition and extrusion-induced thermal effects, and (2) to isolate VOCs associated with the tubing's service-life exposure to battery cooling fluids (application-related contaminants). To this end, the list of identified substances was cross-checked between the virgin reference and the PCR tubing at each tested condition. Compounds detected in both materials were considered representative of the baseline ("blank") VOCs profile, i.e., species inherent to the polymer and/or generated during melt processing. In contrast, compounds detected only in the PCR tubing (and not present in the virgin reference under comparable processing conditions) were classified as application-related contaminants, associated with contact with the cooling liquid and service environment. Based on this classification, two decontamination efficiencies were calculated: (i) an efficiency associated with the removal of the baseline VOCs fraction (polymer/processing-related), and (ii) an efficiency associated with the removal of application-related contaminants specific to the

PCR tubing. For each fraction, an overall decontamination efficiency was calculated from the summed VOC concentrations as:

$$\text{Decontamination efficiency (\%)} = \left(1 - \frac{\sum C_{final}}{\sum C_{Initial}}\right) * 100$$

where $\sum C_{initial}$ corresponds to the total concentration of the selected VOCs group before treatment, and $\sum C_{final}$ corresponds to the total concentration after extrusion at the corresponding CO₂ ratio. The results obtained for VOCs related to scenario (i) baseline VOCs fractions are presented in Figure 5 and Figure 6, respectively.

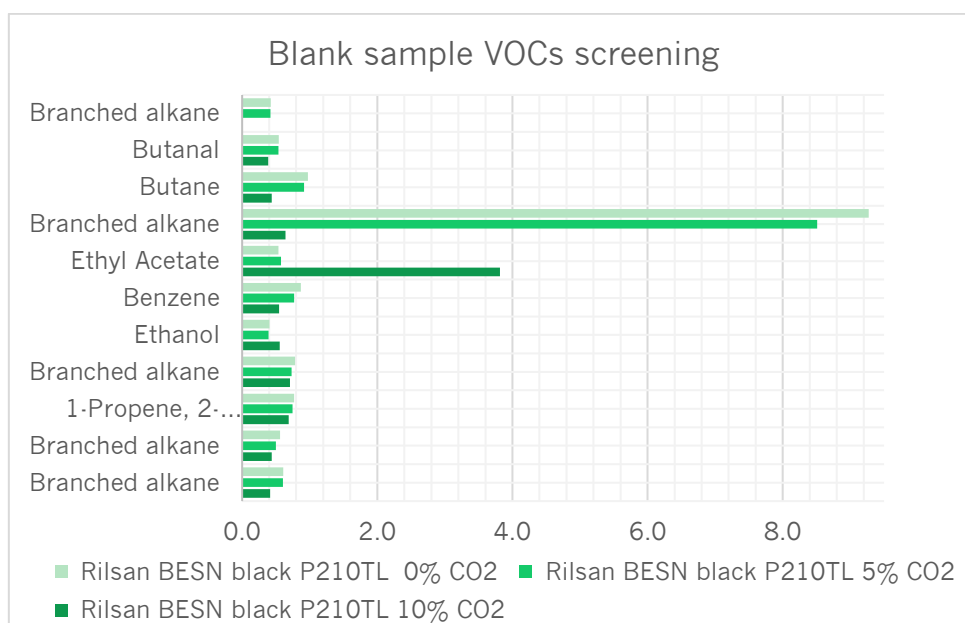


Figure 5. Blank sample VOCs GC-MC results.

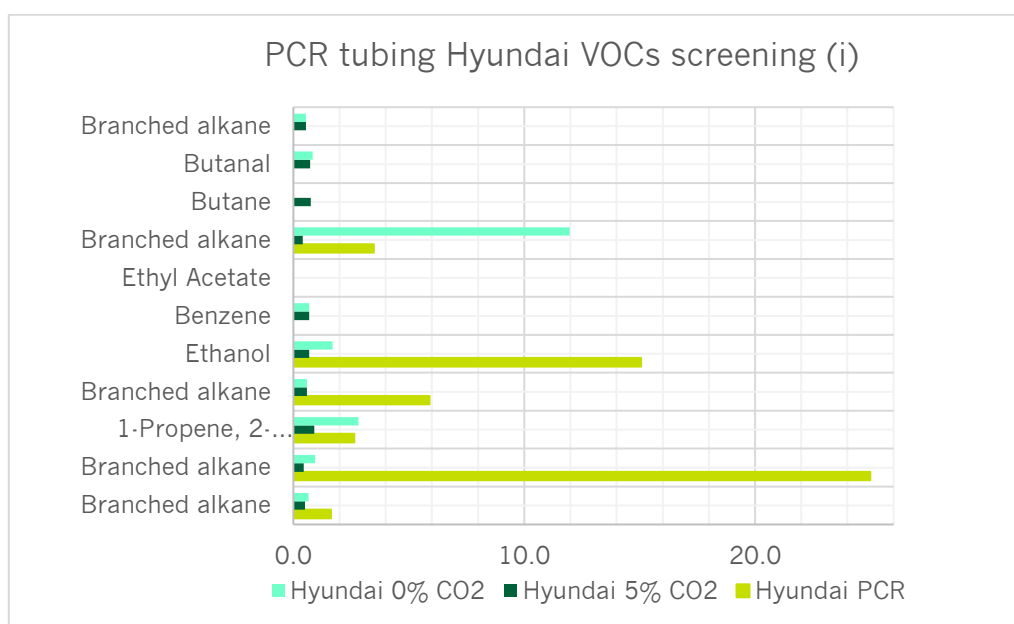


Figure 6. PCR tubing sample baseline VOCs GC-MC results.

Considering the previous results, it is observed that among the analysed substances, specifically butanal, butene and benzene, these compounds are generated during the extrusion process (see Figure 7 for comparison), whereas the remaining substances were already present in the initial PCR sample. For these baseline contaminants, a higher removal efficiency is consistently observed when applying 5 wt.% CO₂ during the stripping step compared to processing with vacuum degassing only (denoted in the graph as 0% CO₂). This confirms the enhanced decontamination efficiency achieved through SC-CO₂-assisted stripping. The efficiency values obtained for each case are reported Table 5:

Table 5. Decontamination efficiencies for the removal of baseline VOCs fraction.

Sample	$\Sigma \text{VOCs}_{\text{initial}}$ (mg/kg sample)	$\Sigma \text{VOCs}_{\text{final}}$ (mg/kg sample)	Decontamination efficiency (i) (%)
Rilsan Black P210 10% CO ₂	15,74	8,62	45,24
PCR HYUNDAI 0% CO ₂	53,7 ⁶	20,74	61,38
PCR HYUNDAI 5% CO ₂	53,7	6,23	88,40

In the second stage, attention was focused on contaminants absorbed during use, particularly those originating from the battery cooling fluid circulating through the PCR Hyundai Tubing. The results obtained as well as efficiencies of decontamination, is presented in Figure 7. It should be noted that the

⁶ ΣC targeted VOCs in PCR tubing sample

detected compounds were only present in the PCR resin and were effectively removed through both vacuum degassing and CO₂-assisted stripping.

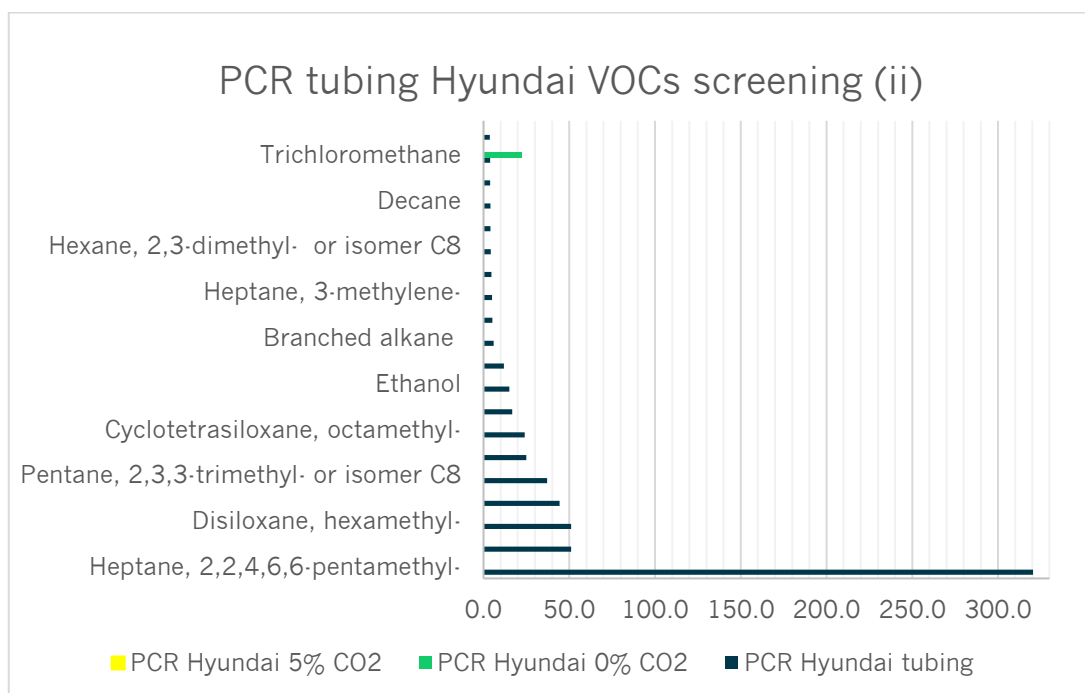


Figure 7. PCR tubing sample application-related VOCs GC-MC results.

Regarding efficiency calculation, in this scenario the result obtained can be seen in

Table 6:

Table 6. Decontamination efficiencies for the removal of application-related VOCs fraction.

Sample	$\sum \text{VOCs}_{\text{initial}}$ (mg/kg sample)	$\sum \text{VOCs}_{\text{final}}$ (mg/kg sample)	Decontamination efficiency (ii) (%)
PCR HYUNDAI tubing	698,71	22,19	96,82

Overall, the results obtained in this study demonstrate that SC-CO₂-assisted melt stripping is an effective and selective decontamination strategy for recovered PA11 cooling tubes from battery systems. The process enables a significant reduction of both baseline polymer-related VOCs and application-related contaminants originating from battery cooling fluids, while preserving the rheological and mechanical integrity of the material when operated within the identified stability limits. The combined analysis of process stability, melt flow behaviour, mechanical performance and VOC removal efficiency confirms that a CO₂/polymer ratio of 5 wt.% represents an optimal compromise between decontamination efficiency and process robustness for the recovered PA11. These findings validate the suitability of the decontaminated recyclates for

subsequent upcycling and reintroduction into high-value applications within the FREE4LiB framework.

3.2. Upcycling of thermoplastic compounds for reuse in new applications.

Following the successful recovery and decontamination of thermoplastics from end-of-life (EoL) EV battery components, the next stage of Task 4.5 focused on enhancing the performance and functional properties of these materials through upcycling. This step is crucial to bridge the quality gap between recycled and virgin polymers and to enable their reintegration into technically demanding applications.

Within FREE4LiB, the upcycling workflow was implemented at pilot scale, using different co-rotating twin-screw extruders designed for controlled dispersion of additives and efficient melt homogenisation. The process was tailored to each polymer type, optimising feed composition, screw configuration, and temperature profiles to achieve the desired balance between stiffness, impact resistance, and processability. The definition of representative case studies was based on three key criteria:

- Functional relevance of the component within the battery pack (structural, protective, or fluidic function).
- Availability and homogeneity of recovered plastic fractions suitable for reprocessing.
- Feasibility of scaling the process to pilot and industrial levels under the operational conditions of Task 4.5.

Accordingly, three upcycling cases were selected to demonstrate the versatility of the approach:

- ✓ Case Study #1: Cell pouch frames (PPE-based material) from battery modules.
- ✓ Case Study #2: Cooling system tubes (PA11/PA66-based material).
- ✓ Case Study #3: Protective and insulating panels (EPP/PP-based material).

For each case, benchmark formulations were developed by combining recycled polymers with virgin grades or tailored additives to compensate for degradation effects identified in WP3. Material pre-treatments such as shredding, homogenisation, and moisture removal were carried out to ensure consistent feeding and process stability during compounding. The resulting upcycled compounds were then characterised through mechanical, thermal, and rheological testing,

providing the baseline for comparative performance assessment against commercial reference grades.

3.2.1. Case study #1 Cell pouch frames

The first case study focused on the upcycling of polyphenylene ether (PPE) recovered from cell pouch frames used in EV battery modules. These components are injection-moulded structural parts designed to support and insulate the pouch cells within the module assembly (Figure 8). Previous investigations under Task 3.5 demonstrated that the recovered PPE retained acceptable stiffness and dimensional stability but exhibited moderate decreases in tensile and flexural strength compared to the virgin benchmark (NORYL™ NHP6012). In parallel, the recycled material showed increased impact strength, suggesting that the polymer network had undergone partial chain relaxation during service life and thermal ageing.

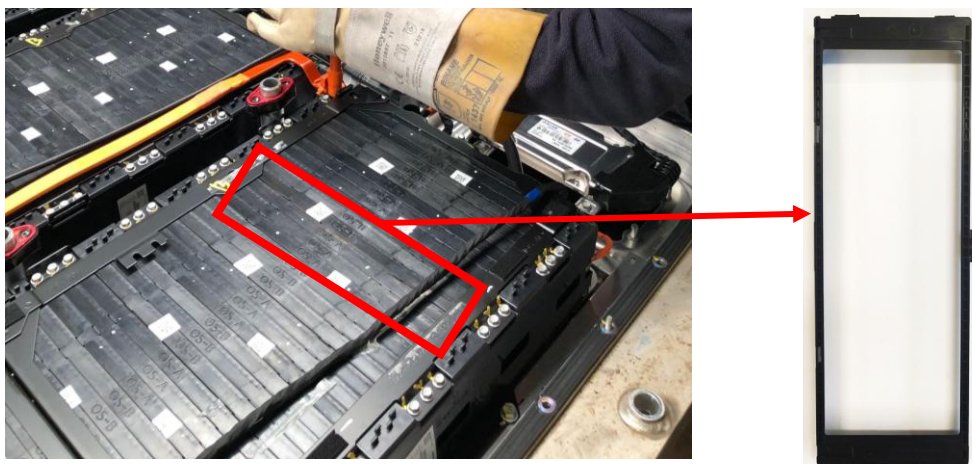


Figure 8. Cell pouch frames from battery packs

The aim of this upcycling activity was therefore to develop reformulated PPE-based compounds capable of restoring or enhancing the mechanical and processing performance of the recycled polymer, enabling its reuse in structural applications with equivalent reliability to virgin materials.

3.2.1.1. Experimental approach.

Recovered PPE granulates obtained after pre-treatment and metal removal were compounded at pilot scale using a co-rotating twin-screw extruder (Figure 9). The upcycling strategy was based on blending the recycled fraction (rPPE) with virgin PPE resin in different proportions — 25%, 50%, and 75% rPPE — to evaluate the optimal ratio for achieving the target property balance. To further improve formulation performance, glass fibres and styrene-based copolymers were introduced via masterbatch during compounding. Glass fibres were added to compensate for stiffness and dimensional stability losses, while

styrene copolymers acted as compatibilizers and impact modifiers, improving interfacial adhesion and melt flow behaviour.



Figure 9. Double screw extruder pilot scale.

Processing parameters such as screw speed, temperature profile, and feeding rate were optimised to ensure homogeneous dispersion of fillers and additives while avoiding thermal degradation of the PPE matrix. The pellets obtained for each formulation can be seen in Figure 10:

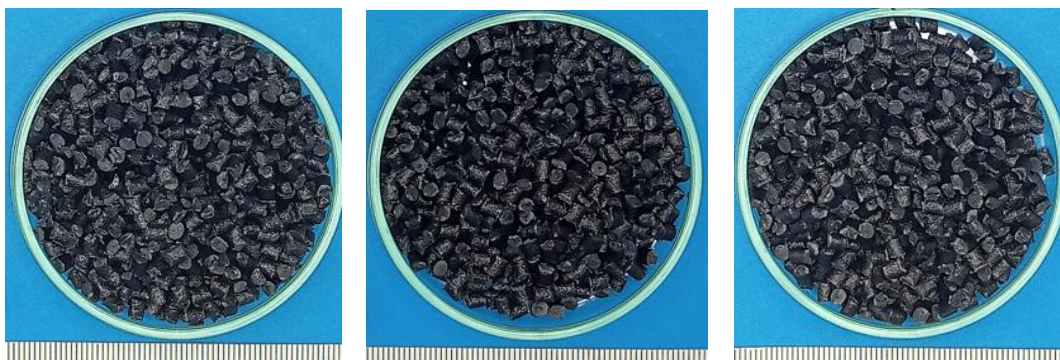


Figure 10. Upcycled PPE pellets made of 25%, 50% and 75% recycled content from left to right.

Each sample was injected into testing bars ISO A to perform mechanical characterization. A benchmarking against reference material (NORYL™ NHP6012) was established to determine the most suitable formulation, with a criterion of maximum 25% delta loss of performance respect control sample. This is a general benchmark of the industry in terms of performance and threshold of recyclates.

3.2.1.2. Material characterization.

Each formulation was injection-moulded into ISO Type A test specimens for comprehensive mechanical characterisation. A benchmarking assessment was

performed against the reference material (NORYL™ NHP6012) to identify the most suitable formulation in terms of mechanical and processing performance. The evaluation followed an industrial performance criterion, setting a maximum acceptable deviation of 25% from the reference properties, which represents a commonly adopted threshold in the sector for qualifying recycled or upcycled polymer grades for technical applications.

Table 7. Upcycled PPE material properties characterization.

Property	Test method	Unit	Benchmark polymer NORYL™ RESIN NHP6012 10% GF	rPPE from EV battery module frames	25% rPPE from EV battery module frames	50% rPPE from EV battery module frames	75% rPPE from EV battery module frames
Tensile stress at break	UNE-EN ISO 27	MPa ⁷	82	78,1±0,5	82,1±0,2	78,5±0,5	73,1±0,4
Tensile strain at break	UNE-EN ISO 27	%	2,5	3,1±0,2	3,2±0,3	3,4±0,1	3,2±0,3
Flexural modulus	UNE-EN ISO 178	MPa	4000	4050±50	4200±30	4100±30	3970±150
Flexural strength	UNE-EN ISO 178	MPa	132	118±1	133±1	126±1	117±1
Charpy impact resistance Notch @ 23°C	UNE-EN ISO 179/1eA	kJ/m ²	6	9,6±0,2	5,9±0,2	6,1±0,3	6,6±0,4
Charpy impact resistance Un-notched @ 23°C	UNE-EN ISO 179/1eU	kJ/m ²	25	34,6±1	34,1±2	34,4±2	35,4±2
Heat Deflection Temperature 1,8 MPa	UNE-EN ISO 75	°C	125	122±1	124±1	120±1	119±1
Heat Deflection Temperature 0,45 MPa	UNE-EN ISO 75	°C	132	128±1	130±1	129±1	126±1
Rockwell M hardness	UNE-EN ISO 2039	..	90	167±2	91±1	84±1	78±2

The comparative analysis between the reference material (NORYL™ NHP6012), the recovered PPE, and the three upcycled formulations containing 25%, 50%, and 75% rPPE clearly demonstrates that the mechanical integrity of the recycled polymer can be effectively restored through appropriate blending and compounding strategies.

⁷ No standard deviation available on supplier' sTDS

In terms of tensile and flexural behaviour, the formulation containing 25% rPPE exhibited a tensile strength (82,1 MPa) virtually identical to the virgin benchmark (82 MPa) and a slightly higher flexural modulus (4200 MPa), indicating full recovery of stiffness and load-bearing capacity. Increasing the recycled content to 50% rPPE resulted in only minor reductions in tensile (−4,3%) and flexural (−4,5%) strength relative to the virgin grade, both values remaining well within the industry-accepted performance deviation of 25%. In contrast, the formulation with 75% rPPE showed a more pronounced decline in these properties (around 10–11% loss), approaching the lower limit for structural applications. These results confirm that incorporation levels up to 50% rPPE maintain mechanical performance comparable to the reference material, ensuring sufficient strength and rigidity for reuse in technical components.

On top of that, the impact performance of the upcycled compounds was also well preserved, with notched and unnotched Charpy impact resistance values remaining stable or slightly improving as the recycled fraction increased. This behaviour suggests that the upcycling process did not compromise toughness; on the contrary, it may have enhanced the material's ability to dissipate energy under impact loading. Such an effect is likely related to the minor morphological heterogeneities introduced during reprocessing, which can act as controlled energy absorbers and contribute to improved ductility.

Regarding thermal performance, the heat deflection temperature (HDT) of the upcycled materials decreased only marginally with increasing recycled content. At a load of 1.8 MPa, HDT values shifted from 125 °C for the virgin grade to 124 °C and 120 °C for the 25% and 50% rPPE compounds, respectively representing less than 4% deviation. The 75% rPPE formulation reached 119 °C, which, although still acceptable for many technical uses, could restrict its applicability in high-temperature environments. Overall, these findings indicate that thermal stability is preserved up to at least 50% rPPE incorporation, supporting its suitability for most EV structural and functional components.

3.2.1.3. Demonstration up-scaling

To validate the industrial feasibility of the upcycled compound, a demonstration injection-moulding trial was conducted using the formulation containing 50% rPPE, previously identified as the optimal composition in terms of mechanical and thermal performance. A prototype mould was designed in AutoCAD, geometrically analogous to the recovered cell pouch frames but scaled down to a reduced-size injection mould to enable controlled process validation and efficient material use (Figure 11).



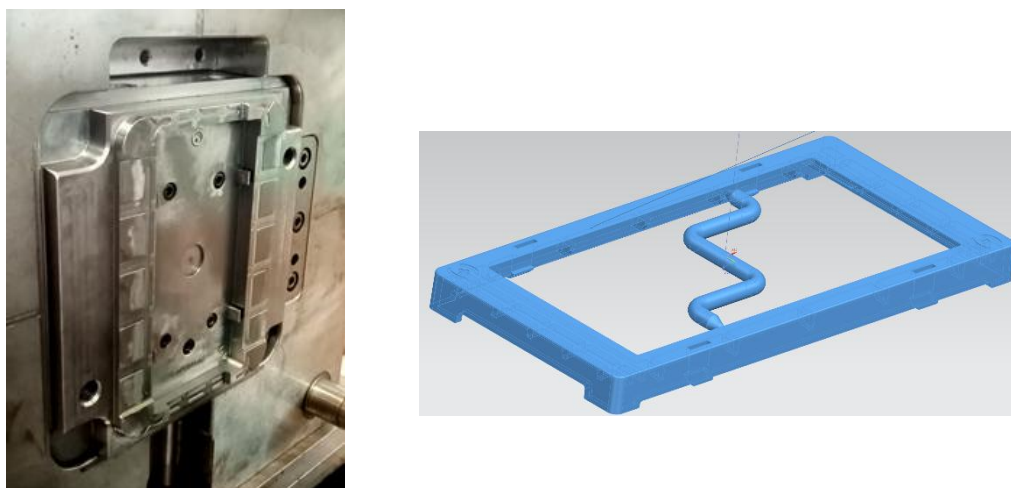


Figure 11. Injection mould design and assembly.

The compounded material was successfully injection-moulded into demonstration plaques with dimensions of $16 \times 8 \times 1,5$ cm (Figure 12), representing the geometry and wall-thickness conditions typical of the original application. The moulded parts exhibited excellent surface finish, dimensional accuracy, and thermal stability, confirming that the upcycled formulation can be processed on standard industrial equipment without evidence of degradation or flow instabilities.

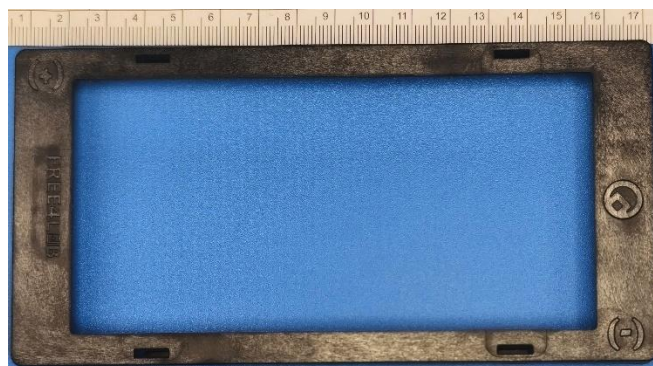


Figure 12. Injection-moulded demonstration frame (50% rPPE compound) – validation of upcycled PPE formulation for circular application in EV battery systems.

The measured density of the material was $1,19 \text{ g/cm}^3$, with an average part volume of $24,0 \text{ cm}^3$ and a weight of approximately 28,5 g (including runner). These physical parameters, along with the mechanical and thermal properties previously reported in Table 7, provide a complete validation of the compound's performance and its suitability for reuse in structural and functional components.

This demonstration represents an essential step toward the industrial up scaling and circular reintroduction of high-performance thermoplastics in the mobility sector. The successful injection-moulding of the 50% rPPE compound

confirms its compatibility with existing processing infrastructure and supports its potential integration into new electric vehicle battery systems. The validated material will be transferred to AVL and EURECAT for further evaluation within the final battery demonstrator, thereby closing the material loop from recovery to re-use.

3.2.1.4. Additive manufacturing demonstration using upcycled PPE compounds.

In addition to the injection-moulding validation activities described in the previous section, an exploratory demonstration of additive manufacturing was carried out to further assess the versatility and application potential of the up-cycled PPE-based compounds.

For this purpose, the upcycled formulation containing 50 wt.% recycled PPE, previously identified as the optimal composition and validated through injection-moulded demonstrators, was selected as feedstock. The same pellets obtained during the upcycling campaign (see Figure 10) were subsequently processed to produce 1,75 mm filament suitable for fused filament fabrication (FFF) 3D printing.



Figure 13. Filament 1,75 mm for 3D printing, made of 50% PCR PPE

The filament production was performed without additional formulation changes, with the sole objective of demonstrating processability into a continuous filament geometry compatible with standard additive manufacturing equipment. No mechanical or thermal characterisation was conducted at this stage, as the activity was conceived as a preliminary demonstration rather than a full qualification exercise.

The produced filament will be supplied to the project partner AVL, who will evaluate its suitability for the fabrication of selected components by 3D printing within the sustainable mobility demonstrator developed in FREE4LiB. This activity aims to explore additive manufacturing as a complementary processing route for upcycled engineering thermoplastics, potentially enabling increased

design flexibility, reduced material waste, and alternative manufacturing pathways for recycled polymers in future EV applications

3.2.2. Case study #2 Pipes and tubes cooling system

Cooling system tubing made of PA11 underwent supercritical CO₂ decontamination (see Subtask 4.5.1) and was then extruded into new tubing prototypes. The aim was to demonstrate that recycled and decontaminated PA11 can be potentially reintroduced into closed-loop cooling applications, provided that long-term durability tests validate their performance. The Upcycling workflow is represented in Figure 14:

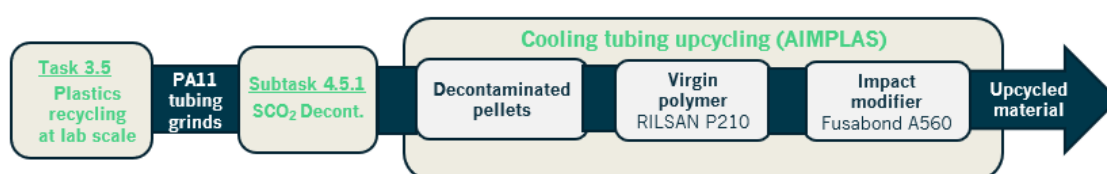


Figure 14. Upcycling workflow PA11 cooling tubes.

Final tubes will be characterised to assess their performance and to propose any necessary formulation changes aimed at enhancing their physical and mechanical properties.

3.2.2.1. Experimental approach.

PA11 tubing previously decontaminated and mechanically characterised (see Table 4) was further processed following an upcycling approach aimed at pipe-to-pipe reintroduction. The objective of this experimental work was to obtain compounded materials suitable for extrusion into new tubing prototypes and to evaluate their processability and performance in a finished-product application.

As a first step, a reference recycled PA11 material (rPA11) was prepared by reprocessing the virgin grade RILSAN® B210 Black under controlled extrusion conditions. This step was intended to simulate the thermal history of a pre-consumer recycled material, enabling its subsequent blending with the decontaminated PA11 flakes and allowing a more realistic benchmark against the recovered PCR PA11. The reprocessing was carried out at a melt temperature of 247 °C, using a barrel temperature profile in the range of 210–230 °C. The resulting pellets were subsequently used as reference rPA11 material for tubing applications, together with decontaminated PCR PA11 pellets.

In a second step, a compounded formulation was prepared to assess the effect of impact modification on the addition to rPA11 material.



Figure 15. Upcycling process of decontaminated PA11 pellets via extrusion compounding.

A total batch of 2,5 kg was produced for each formulation, including reprocessed virgin polymer RILSAN, and the modified mixed consisting of rPA11 (recycled and decontaminated material) and impact modifier FUSABOND® A560, corresponding to a content of 80/20 wt.% (refer to Table 8). Compounding was performed in a twin-screw extruder under processing conditions representative of industrial practice, (see machinery set up in Figure 15).

Table 8. Upcycled materials obtained via extrusion compounding.

Sample	rPA11 content (wt.%)	Impact modifier (FUSABOND® A560) (wt.%)	Total, batch size (kg)	Processing observations
rPA11 obtained from RILSAN® B210 Black	100	0	2,5	Stable processing conditions
Reprocessed decontaminated rPA11 with impact-modifier	80	20	2,5	Some fumes observed and controlled via degassing

During compounding, an average torque of approximately 68% and a melt pressure of around 30 bar were recorded, indicating stable processing behaviour. Gas evolution was observed particularly in sample *Reprocessed decontaminated rPA11 with impact-modifier* during extrusion, likely associated with residual volatiles or additive-related outgassing, and was managed through the extruder's degassing system. Following compounding, pellets obtained were subjected to compression-moulding to obtain standardised test specimens for mechanical characterization. The results are compiled in Table 9:

Table 9. Mechanical characterization of decontaminated PCR Hyundai tubing samples

Property	Test method	Unit	PCR HYUNDAI tubing 5% CO ₂	rPA Rilsan Black P210	PCR Hyundai +20% Impact modifier
Tensile Modulus	UNE-EN ISO 527-2	MPa	518±48	685±8	446±8

Yield Stress	UNE-EN ISO 527-2	MPa	26,7±1	36,1±0,7	21,5±0,8
Yield Strain	UNE-EN ISO 527-2	%	37±1	37±2	21±2
Nominal strain at break	UNE-EN ISO 527-2	%	180±20	150±10	26,7±1
Charpy impact resistance Notch @ 23°C	UNE-EN ISO 179/1eA	kJ/m ²	86,7±5	61,6±7	78±11
Charpy impact resistance notch @ -30°C	UNE-EN ISO 179/1eU	kJ/m ²	11,9±0,9	7,6±1	9,9±3

The mechanical performance was analysed by comparing the decontaminated PCR PA11 tubing, the reprocessed PA11 reference material (rPA11) and the impact-modified PCR formulation, with the objective of assessing the overall balance of properties and determining whether the incorporation of an impact modifier provides a tangible benefit for pipe-to-pipe upcycling applications. The decontaminated PCR Hyundai PA11 tubing processed with 5 wt.% CO₂ exhibits a well-balanced mechanical profile. Although its tensile modulus is lower than that of the reprocessed rPA11, it shows significantly higher ductility, as evidenced by increased yield strain and a markedly higher nominal strain at break. This behaviour reflects enhanced flexibility and toughness, which are key requirements for tubing applications subjected to deformation, vibration and cyclic mechanical loading. In addition, the PCR material demonstrates superior impact resistance at both room temperature and -30 °C compared to rPA11, confirming that the SC-CO₂ decontamination and reprocessing steps do not negatively affect, and may even enhance, impact performance.

In contrast, the reprocessed rPA11 exhibits higher stiffness and yield stress; however, this improvement in rigidity is accompanied by a reduction in impact resistance, particularly at low temperature. This combination indicates a stiffer but more brittle material, which may limit its applicability in cooling system components where resistance to impact and flexibility are critical.

The impact-modified PCR formulation containing 20 wt.% FUSABOND® A560 shows a pronounced decrease in tensile modulus and yield stress compared to both the decontaminated PCR material and rPA11. While impact resistance remains comparable to that of the unmodified PCR formulation, no significant overall improvement in mechanical performance is observed. Moreover, the reduced elongation at break suggests that the high impact modifier content may disrupt the continuity of the PA11 matrix. This interpretation is consistent with the gas evolution observed during compounding, pointing to limited compatibility and processing challenges at the selected modifier concentration.

Overall, the comparative analysis indicates that the decontaminated PCR PA11 tubing exhibits the most favourable balance of mechanical properties among the materials studied, combining adequate stiffness with high ductility and impact resistance. Under the conditions investigated, the addition of 20 wt.% impact modifier does not provide a clear performance advantage and therefore does not appear necessary for the intended pipe-to-pipe upcycling application.

3.2.2.2. Demonstration up-scaling

To assess the upscaling potential and industrial processability of the upcycled PA11 materials, a tubing extrusion demonstration was carried out using the previously characterised pellet formulations. The objective of this activity was to validate the feasibility of processing recycled and decontaminated PA11 into hollow tubing using conventional extrusion technology, while evaluating melt stability, dimensional consistency and surface quality. The piping extrusion line can be seen in Figure 16.



Figure 16. Piping extrusion line.

Tubing extrusion trials were performed to produce hollow tubes with an outer diameter of 5 mm and a wall thickness of 1 mm, representative of small-diameter cooling system components. Several formulations were processed in order to compare their extrusion behaviour and final appearance:

- 100 wt.% rPA11 Rilsan (reprocessed reference material).
- 50/50 blend of rPA11 Rilsan and PCR PA11 tubing, combining pre- and post-consumer recycled content.
- Impact-modified formulation, consisting of 80 wt.% PCR PA11 and 20 wt.% impact modifiers.

The results samples and results obtained for each material is compiled in Table 10.

Table 10. Tubing validation of upcycled PA for circular application in EV battery systems.

Sample ID	Torque (A)	Melt temperature (°C)	Melt pressure (bar)	Picture
rPA11 RILSAN® B210 Black	9,6	188	353	
50/50 blend of rPA11 Rilsan and PCR PA11 tubing	6,1	191	189	
PCR Hyundai tubing+ 20% impact modifier	6,4	202	189	

Based on the extrusion outputs obtained, the 50/50 blend of PCR PA11 and rPA11 was processed under stable conditions, achieving consistent tube geometry and wall thickness. This demonstrates the technical feasibility of incorporating up to 50 wt.% of post-consumer recycled material recovered from real cooling tubing, together with 50 wt.% of pre-consumer recycled PA11, resulting in a formulation with 100% recycled content. In line with the project KPIs, the target incorporation level of 50–70% recycled material was successfully met, and the tubing application was validated at TRL 6.

3.2.3. Case study #3 Protective and insulating panels

Expanded polypropylene (EPP) foams recovered from end-of-life EV battery packs were selected as a representative case for evaluating the upcycling



potential of lightweight insulation components as reported in Task 3.5, which combine energy absorption, thermal insulation, and mechanical protection functions. The recovered panels can be seen in Figure 17.

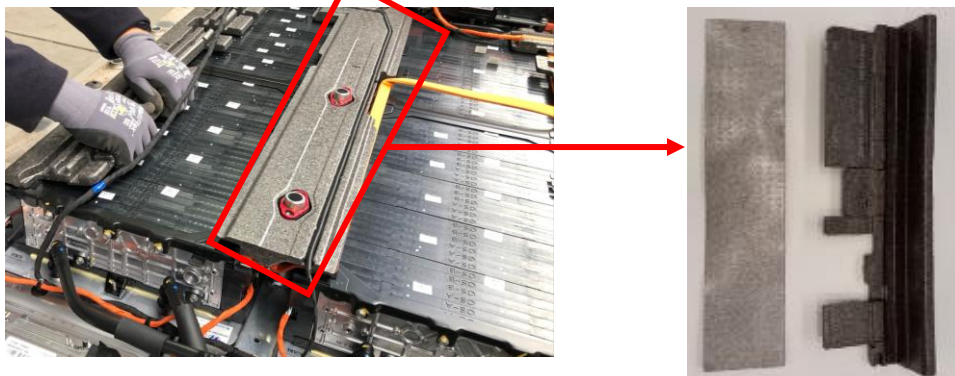


Figure 17. EPP insulating panels from battery packs.

The upcycling study aimed to determine whether recycled polypropylene (rPP) derived from EPP waste could be reintroduced into high-melt-strength (HMS) PP matrices while maintaining the mechanical and morphological characteristics required for technical foamed applications.

3.2.3.1. Experimental approach.

To this end, the recovered panels mechanically shredded and densified, were processed by tandem extrusion foaming using a Promix CO₂ injection system as a physical blowing agent. The foaming trials were conducted on a dual-extruder line (Figure 18) equipped with dedicated foaming screws and a die head. Each formulation included 4 wt.% of nucleating agent (Granic 1051, PP base) and varying proportions of recycled PP (10%, 20%, and 30%) blended with Daploy™ WB149HMS virgin resin.

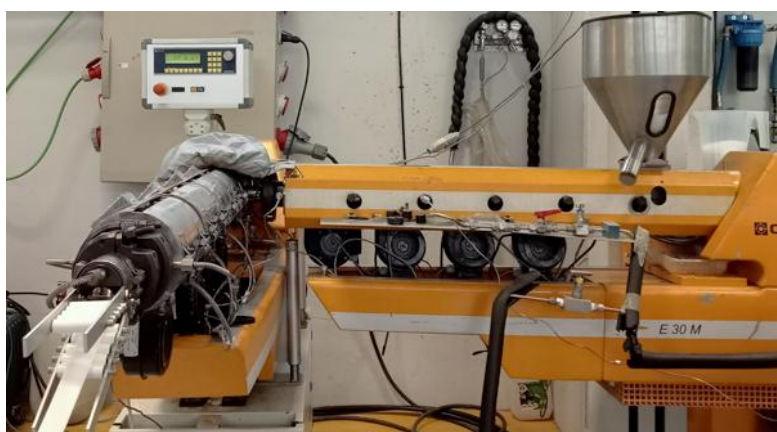


Figure 18. Tandem extrusion foaming system.

Processing parameters were adjusted to maintain stable melt conditions, with a melt temperature of 190–191 °C, and CO₂ injection rates of 200–250 g/h. The CO₂ feed pressure was gradually increased with recycled content to

compensate for viscosity loss and to promote uniform cell nucleation. Observations during the trials confirmed that foaming stability decreased slightly with higher rPP content, requiring tighter control of temperature and gas flow. Nevertheless, foams with up to 30% rPP could be produced successfully in 3 kg batches (Figure 19).

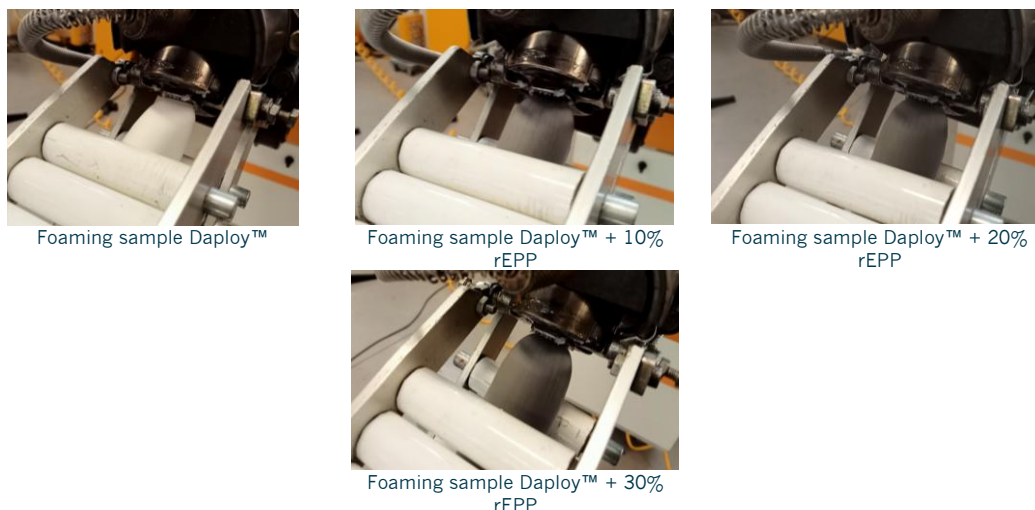


Figure 19. Foaming extrusion die.

From a processing standpoint, the optimum CO₂ flow rate was established at 250 g/h, with a total material throughput of approximately 3,5 kg/h. Qualitatively, the recycled formulations showed unexpectedly higher melt resistance, contributing positively to foam formation and dimensional control, although at the expense of process stability.

3.2.3.2. Material characterization.

Microscopic and physical analyses were carried out to evaluate the effect of recycled content on cell size and distribution. The reference HMS-PP (pure Daploy™) presented a mean pore diameter of 0,313 mm (maximum 0,557 mm) with uniform, closed-cell morphology. The introduction of recycled PP up to 10% increased the mean pore diameter slightly to 0,363 mm, without significant loss of uniformity. Figure 20 and

Table 11 show the pore diameter distribution obtained for each sample.

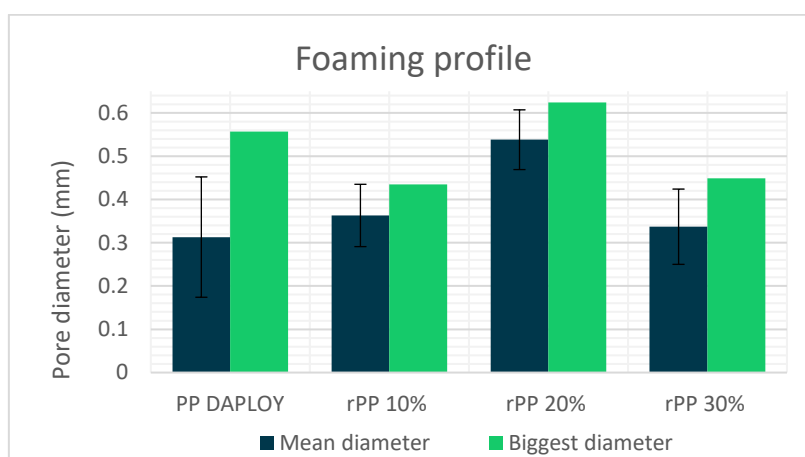


Figure 20. Average foaming profile for each sample.

Table 11. Physical analysis characterization

Description	Mean diameter (mm)	Biggest diameter (mm)
PP DAPLOY™	0,313 ± 0,139	0,557
rPP 10%	0,363 ± 0,072	0,435
rPP 20%	0,538 ± 0,069	0,624
rPP 30%	0,337 ± 0,087	0,449

At 20% rPP, the mean pore d. rose to 0,538 mm (maximum 0,624 mm), indicating enhanced gas expansion and lower melt strength - typical of partial chain scission in the recycled phase (Figure 21). Although pore coalescence was observed locally, the resulting foams maintained structural integrity and intermediate density, making them suitable for lamination and semi-structural applications.

Conversely, the 30% rPP formulation yielded a denser foam with a smaller average pore size (0,337 mm) and maximum diameter of 0,449 mm, suggesting premature cell collapse during expansion due to reduced viscoelastic recovery. Despite its increased stiffness and dimensional stability, this grade exhibited limited insulation performance compared to lower-density formulations.

The correlation between cell morphology and bulk density reinforces these observations. As summarised in Table 12, density increases progressively with higher recycled content, ranging from 139,6 kg/m³ for the reference HMS-PP to 457,1 kg/m³ for the 30% rPP formulation. This trend reflects the reduced foaming efficiency of the blends containing higher rPP fractions, where degraded molecular architecture and lower melt elasticity hinder gas retention and expansion. In contrast, the intermediate formulation containing 10–20% rPP reached densities between 182–250 kg/m³, corresponding to an optimal compromise between cell growth, mechanical cohesion, and insulation efficiency.

Table 12. Bulk density characterization results.

Description	Bulk density (kg/m ³)
PP DAPLOY™	139,6 ± 6,7
rPP 10%	182,2 ± 12,0
rPP 20%	249,5 ± 9,0
rPP 30%	457,1 ± 5,8

From a materials science perspective, the simultaneous analysis of cell size distribution and bulk density confirms the critical influence of melt viscoelasticity on foam morphology. As recycled content increases, the reduced chain entanglement and molecular weight lead to higher gas diffusion rates and less stable bubble growth, which translates into smaller pores and higher apparent density. The results thus indicate that an incorporation level of 10–20% rPP maintains sufficient melt strength to support uniform foaming while preserving lightweight and insulating characteristics, whereas higher contents shift the balance toward densification and structural rigidity.

3.2.3.3. Demonstration up-scaling.

The upcycling trials performed on EPP-derived polypropylene foams represent a proof of concept for evaluating the recyclability and technical feasibility of reintroducing post-consumer foamed materials from EV battery packs into new high-melt-strength polypropylene (HMS-PP) formulations. The initial target was to achieve at least 50% recycled content while maintaining comparable processability and structural integrity to virgin HMS-PP grades.

The results demonstrate that stable and homogeneous foams could be obtained up to 20% recycled content, validating the technical feasibility of partial reintegration of EPP recyclates. Within this range, the materials displayed an appropriate balance between cell regularity, melt strength, and density (182–250 kg/m³). Microscopic analyses confirmed that at 10–20% rPP, the cell structure remained regular, with mean pore diameters between 0,36 mm and 0,54 mm, ensuring good insulation and mechanical cohesion (see Figure 21).

When increasing the recycled fraction to 30% or above, however, the foaming behaviour degraded markedly. The samples exhibited cell collapse, irregular morphology, and increased bulk density (≈ 457 kg/m³), linked to reduced melt elasticity and molecular degradation of the recycled phase. These effects prevented achieving the target of 50% recyclates incorporation, as the material performance and process stability fell below the thresholds required for technical-grade foam applications. Therefore, while the concept was successfully validated, the quantitative KPI of recyclates incorporation was not fulfilled under current conditions. To enhance recyclates integration and foam

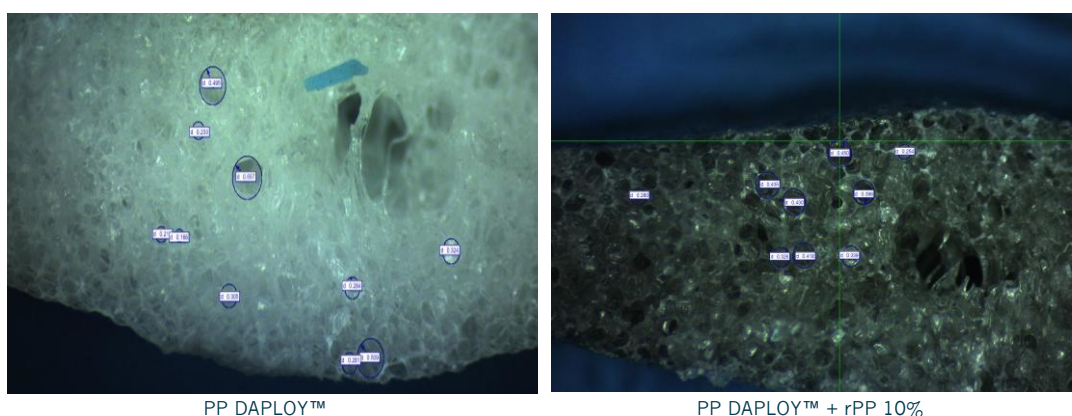
performance, several optimisation strategies are proposed for future research and industrial validation:

- Inclusion of alternative organic nucleating agents (e.g. talc, sodium benzoate, or sorbitol derivatives) to promote uniform cell nucleation and refine pore morphology.
- Incorporation of rheology modifiers or nanofillers (e.g. nano clays, silica, or long-chain branching agents) to improve melt elasticity during gas expansion.

Such approaches, widely adopted in industrial HMS-PP foaming, could allow higher recyclates incorporation levels (30–50%) while maintaining structural and insulation properties comparable to virgin-based materials. Nonetheless, the cost effectiveness shall be considered in detail to validate the alternative.

Although the overall mechanical and morphological properties achieved at 10–20% rPP content are promising for lightweight insulation and protective panels, the limited material quantity produced (≈ 3 kg) and its non-optimal surface and density uniformity restrict its suitability for integration into the final project demonstrator. Consequently, the material will not be supplied to AVL or EURECAT for inclusion in the FREE4LiB battery prototype.

Nonetheless, the trials provide valuable empirical data on the processing limits, morphological evolution, and structure–property relationships of recycled EPP foams. These findings contribute to the project KPIs by validating the technical viability of recycling and upcycling routes at pilot scale (TRL 5–6) and by identifying the key technological barriers—notably melt degradation and cell instability—that must be addressed in future industrial optimisation.



PP DAPLOY™

PP DAPLOY™ + rPP 10%

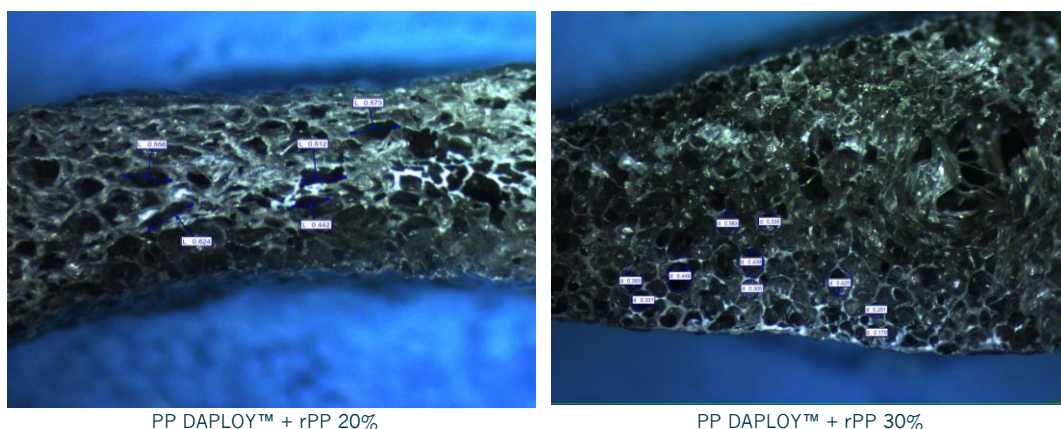


Figure 21. Microscopy images of foamed samples containing 10%, 20%, and 30% rPP showing evolution of pore structure and cell morphology.

4. Conclusions

This deliverable demonstrates the technical feasibility of recycling and upcycling thermoplastics recovered from end-of-life (EoL) electric vehicle (EV) battery systems within the FREE4LiB framework. The work conducted under Task 4.5 addressed two core objectives: the effective decontamination of highly exposed battery plastics and the restoration of their functional performance to enable reintegration into high-value applications.

Supercritical CO₂ (SC-CO₂) melt stripping proved to be an effective and selective decontamination technology for PA11 cooling tubes, achieving removal efficiencies of up to 96.8% for application-related contaminants while preserving polymer integrity when operated within the defined stability window. The decontaminated PA11 showed rheological and mechanical behaviour compatible with subsequent compounding and extrusion, fulfilling the objective of producing high purity recyclates suitable for functional reuse.

The developed upcycling strategies enabled the incorporation of recycled content into demanding battery-related components:

- Case Study #1 (PPE cell pouch frames), compounds containing 50 wt.% recycled PPE met industrial performance criteria and were validated through injection-moulded demonstrators at TRL 6.
- Case Study #2 (PA11 cooling tubes), a 50/50 blend of post-consumer PCR and pre-consumer recycled PA11, corresponding to 100% recycled content, was successfully extruded into new tubing with stable geometry and surface quality, exceeding the project target of 50–70% recycled content and reaching TRL 6.
- Case Study #3 (PP insulation foams), recycled PP could be incorporated at 10–20 wt.% while maintaining acceptable foam structure, but higher contents were limited by melt-strength loss, preventing the achievement of the 50% recycled content KPI.

Several technical constraints relevant for industrial deployment were identified. Recycled PA11 exhibited a narrower processing window under SC-CO₂ than virgin grades, requiring precise control of CO₂ loading to avoid transient overplasticisation and instability. In PP foams, degradation-induced loss of melt elasticity constrained the maximum usable recycled content. In addition, limited availability and heterogeneity of some post-consumer streams (cooling tubing) required blending with pre-consumer recycled material to enable pilot-scale demonstrations, reflecting realistic supply-chain conditions.

Overall, Task 4.5 validated at TRL 5–6 a complete pathway from battery plastic recovery to decontaminated recyclates and functional demonstrators. The results confirm that high-performance polymers from EV batteries—particularly PPE and PA11—can be reintroduced into new battery components with high recycled content and competitive performance, while clearly identifying the remaining technical bottlenecks that must be addressed to further increase circularity in complex polymer systems.

