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Life Cycle Assessment of Pvc Waste: A Case Study of Pvc Automotive Floor Mats From a Circular Economy Perspective

Marcos Vinícius Maceno

mmaceno1987@gmail.com

Federal University of Sao Carlos - Campus Sorocaba: Universidade Federal de Sao Carlos - Campus Sorocaba - CCGT - Centro de Ciências em Gestão e Tecnologia - Sorocaba, São Paulo, BRAZIL
https://orcid.org/0009-0000-7002-3767

João Victor Encide Salla

Federal University of Sao Carlos - Campus Sorocaba: Universidade Federal de Sao Carlos - Campus Sorocaba - CCGT - Centro de Ciências em Gestão e Tecnologia - Sorocaba, São Paulo, BRAZIL

Tiago Barreto Rocha

ACV Brasil, Jundiai, São Paulo, BRAZIL

Jane Maria Faulstich de Paiva

Federal University of Sao Carlos - Campus Sorocaba: Universidade Federal de Sao Carlos - Campus Sorocaba - CCGT - Centro de Ciências em Gestão e Tecnologia - Sorocaba, São Paulo, BRAZIL

Virginia Aparecida da Silva Moris

Federal University of Sao Carlos - Campus Sorocaba: Universidade Federal de Sao Carlos - Campus Sorocaba - CCGT - Centro de Ciências em Gestão e Tecnologia - Sorocaba, São Paulo, BRAZIL

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LIFE CYCLE ASSESSMENT OF PVC WASTE: A CASE STUDY OF PVC AUTOMOTIVE FLOOR MATS FROM A CIRCULAR ECONOMY PERSPECTIVE

Marcos Vinícius Maceno[1] (**Orcid:** 0009-0000-7002-3767); João Victor Encide Salla[1] (**Orcid:** 0000-0003-2693-7742); Tiago Barreto Rocha[2] (**Orcid:** 0000-0002-6445-8315); Jane Maria Faulstich de Paiva[1] (**Orcid:** 0000-0001-8924-6194); Virgínia Aparecida da Silva Moris[1] (**Orcid**: 0000-0002-6374-1792)

[1] Federal University of Sao Carlos - Campus Sorocaba: Universidade Federal de Sao Carlos - Campus Sorocaba - CCGT - Centro de Ciências em Gestão e Tecnologia - Sorocaba, São Paulo BRAZIL

[2] ACV Brasil, Jundiai, São Paulo, BRAZIL

* Marcos Vinícius Maceno: mmaceno@estudante.ufscar.br; mmaceno1987@gmail.com

Abstract

Guidelines such as the Green Mobility and Innovation Program (MOVER) have accelerated the transition toward a circular economy in the Brazilian automotive sector. In this context, a clear knowledge gap was identified in the literature regarding the reuse of polyvinyl chloride (PVC) in this segment, as previous studies have focused mainly on the construction sector. To address this gap, a life cycle assessment (LCA) was carried out using primary data collected from an automotive floor mat manufacturing plant located in the state of São Paulo, Brazil, combined with the application of the Material Circularity Indicator (MCI). The study assessed the incorporation of PVC waste generated during the production process, aiming to promote material loop closure in line with circular economy principles. The modeling results confirmed the environmental feasibility of changing the product composition compared with a scenario based exclusively on virgin material. PVC production was identified as the most critical hotspot; however, its gradual replacement with recycled material reduced the potential impacts in the evaluated categories. The results indicate that recycling enables closed-loop material management and that the combined use of LCA and MCI is essential for holistic assessments, avoiding partial evaluations. In addition to primary data obtained from a relevant company in the sector, this study used the Ecoinvent v3.10 database as a source of secondary data, providing technical and regulatory support for decision-making by industrial managers and public policymakers.

Keywords: circular economy; LCA; PVC; waste; automotive sector; MCI.

1 Introduction

After the Industrial Revolution, mass production systems expanded access to consumer goods, relying primarily on a linear economy model based on “take, make, use, and dispose” (Weetman 2019; Ellen MacArthur Foundation 2025; Purushothaman *et al.* 2025; Teixeira 2025). This culture, based on linear consumption and disposal, has increased waste generation and its associated impacts. In this context, the transition to a circular economy (CE) becomes increasingly important. CE can be defined as a regenerative system in which resource inputs, resource use, emissions, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops (Geissdoerfer *et al.* 2017). This concept is associated with product life cycles (Samani 2023; Khandelwal *et al.* 2025) and sustainability (Geissdoerfer *et al.* 2017; Islam *et al.* 2025), as it aims to reduce waste generation, especially by improving the use of natural resources through the extension of their life cycles.

The world population is estimated to reach almost 10 billion by 2060 (Prochatzki *et al.* 2023), while annual waste generation is expected to increase from 2.1 billion tonnes in 2020 to more than 3.8 billion tonnes by 2050 (United Nations Environment Programme 2024). Therefore, the need to consider circularity has become increasingly urgent. Several countries have developed laws and/or strategies to promote circularity worldwide, including the European Union, China, and Japan (Geissdoerfer *et al.* 2017). In Brazil, the National Solid Waste Policy (PNRS) was approved in 2010 (Brasil 2010), establishing reverse logistics obligations for several waste streams and sectors. In 2024, a decree was approved establishing the National Circular Economy Strategy (ENEC) (Brasil 2024).

Specifically for the automotive sector, Law No. 14,902/2024 (Brasil 2024a), known as MOVER (Green Mobility), was approved, establishing obligations for vehicle manufacturers and importers, considering that this sector accounts for more than 20% of Brazilian industrial GDP (Anfavea 2025). Among these obligations, compliance with product carbon footprint requirements from a cradle-to-grave perspective is emphasized, including recyclability and end-of-life indices for manufactured vehicles. For example, the decree regulating the MOVER law (Brasil 2025) defines that, from 2027 onward, M1 vehicles (conventional passenger cars) manufactured according to ABNT NBR 13776:2021 (ABNT 2021) must be designed to contain at least 80% reusable or recyclable materials in their mass composition. Initiatives such as this clearly show the advancement of policies and debates on circular economy in the automotive sector, raising the need to understand how science has responded to this context.

Based on a literature review, several CE initiatives in the automotive sector were identified, particularly those related to management and practical applications in the sector. In the management field, several studies on electric vehicle batteries were identified, highlighting the need to expand collection infrastructure, standardize dismantling procedures, and even redesign battery packs to facilitate remanufacturing and recycling (Moita *et al.* 2024; Neri *et al.* 2024; Chigbu and Umejesi 2024; Villagrossi and Dinon 2023; Rastegarpanah *et al.* 2021; Hong and Choi 2025).

Still within the management topic, studies focused on end-of-life vehicle (ELV) management were found. Several studies highlighted the emerging nature of the topic; however, vehicle dismantling

techniques still need to evolve to improve material recovery. This process may be accelerated through public policies aimed at the circularity of ELV materials (Karagoz *et al.* 2020; Aggrawal *et al.* 2025; Tarrar *et al.* 2021; Cucchiella *et al.* 2016; Cozza *et al.* 2023).

Other authors have highlighted the importance of digital technologies (Istrițeanu *et al.* 2024) and methodologies such as the 9Rs (refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover), MFA (material flow analysis), life cycle assessment (LCA) (Vogiantzi and Tserpes 2023), circularity indicators such as the MCI (Matos *et al.* 2023; Mansuino *et al.* 2024), lean six sigma integrated with Industry 4.0 concepts (Shrivastava and Mishra 2025), machine learning (Tajally *et al.* 2025), and even Grey-DEMATEL (Bhatia *et al.* 2020; Suman and Rajak 2025) as drivers of CE in the automotive sector.

Takimoto *et al.* (2024) conducted a study showing car sharing as a promising initiative to reduce the need for natural resources. In addition, LCA was highlighted as a useful methodology because it allows the assessment of potential environmental impacts in polymer recycling routes in the automotive sector, such as for polyethylene terephthalate (PET) (Iturrondobeitia *et al.* 2023) and polylactic acid (PLA) (Sibille *et al.* 2025).

Among more practical studies, initiatives were found regarding polymer circularity through the recovery of polyamide 66 (PA66) (Kumar *et al.* 2025), polypropylene (PP) recycling tests from bumper paints (Garcia-Vazquez *et al.* 2023; Membrives *et al.* 2025), polyurethane (PU) recovery from automotive seats (Jung *et al.* 2022), and even the application of plastic waste from the automotive sector in cement for the construction sector (Alonso *et al.* 2025; Roy and Shaik 2025), enabling its use in other cycles.

Other studies have assessed the potential recovery of automotive plastics using 3D printing (Ruiz *et al.* 2022; Laoutid *et al.* 2021; Nguyen *et al.* 2022). Similarly, Arias-Jaramillo *et al.* (2023) assessed the reuse of engine sealing waste in the production of shoe soles. Finally, Coimbra *et al.* (2025) tested the use of recovered carpet as an aggregate in cement.

In summary, the literature shows significant progress in studies involving electric vehicle batteries, ELVs, and circularity assessment frameworks such as the MCI. However, most studies focus on high-value flows or system-level approaches, with limited attention given to specific automotive interior components. Only one study on vehicle floor mats was identified, conducted in Turkey using a cradle-to-gate boundary and within an industrial and regulatory context different from that of Brazil (Örücü and Atilgan Türkmen 2022). In addition, there is a shortage of studies involving circularity and the recovery of polymers used in vehicles, especially polyvinyl chloride (PVC) waste, the fifth most used polymer in the automotive industry (Acc 2024).

Therefore, based on the literature review, a research opportunity was identified regarding automotive PVC waste and, in particular, the composition of vehicle floor mats, which has been little explored in the literature. Considering an annual production capacity of 4.6 million automobiles (Anfavea 2025) and that a set of vehicle floor mats ranges from 2.2 to 5.8 kg per vehicle (Örücü and

Atilgan Türkmen 2022), it is plausible to assume that the annual generation of floor mat waste in Brazil is on the order of millions of kilograms.

In this context, the objective of the present study was to evaluate the reuse of PVC waste from the automotive industry for the production of automotive floor mats. The paper is organized into materials and methods, presentation of results and discussion in relation to the literature, and final considerations, including the main results and challenges observed in the process.

2 Materials and methods

To achieve the proposed objective, two tools were applied to the case study: life cycle assessment and the Material Circularity Indicator (MCI). The LCA study was conducted using a cradle-to-grave perspective and in accordance with ISO 14040 (ISO 2006a) and ISO 14044 (ISO 2006b), being structured into four phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation. In addition to the LCA, the MCI was calculated to complement and compare the LCA results, especially for the climate change category.

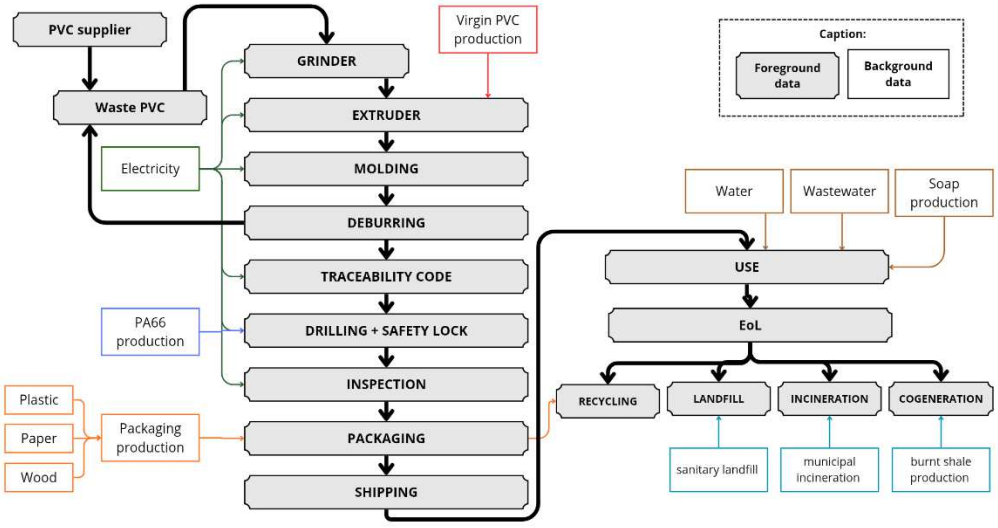
2.1 LCA study

2.1.1 LCA Definition of goal and scope

The objective of the study was to analyze the potential environmental impacts associated with the use of PVC waste generated in the automotive industry. For this purpose, its subsequent use as raw material in the production of PVC vehicle floor mats was considered, reintegrating it into the company that generated the waste. The study aims to assess the life cycle hotspots of the PVC floor mat, considering a cradle-to-grave boundary. The modeling of the floor mat production process used primary data collected from August to October 2025 from an automotive floor mat manufacturing plant located in the countryside of the state of São Paulo, Brazil.

An attributional LCA was used, and the functional unit was defined as one PVC floor mat set weighing 3.34 kg, which also corresponds to the reference flow of the study. The product is intended to protect the original vehicle floor carpet during use. The product system (Figure 1) included the following life cycle stages: production and transformation of raw materials, production of the floor mat set itself, distribution of the finished product, use, end-of-life strategies, and all transportation data related to the life cycle. The study was modeled using OpenLCA v.2.2 and the Ecoinvent v.3.10 database for background datasets.

Fig. 1 Product system and boundaries



Source: Authors.

For the comparative analysis, the scenarios presented in Table 1 were proposed and considered. The scenarios were designed according to variations in PVC raw material composition (i, ii, iii) and floor mat end-of-life (EoL) disposal strategies (iv, v, vi, and vii). For subsequent comparison using the MCI indicator, detailed later, scenario (viii) was proposed; however, it was not included in the comparative LCA impact analyses. All eight scenarios were used for MCI calculation. The baseline scenario (i and iv), i.e., the reference scenario, considered the use of 100% virgin PVC raw material and landfill as the final destination, since this is the main destination for PVC waste.

Table 1 Scenarios

Scenario	Purpose	Raw material (PVC)	End of Life (EoL)
i	Baseline (raw material)	100% virgin	Landfill
ii	Compare raw materials	60% virgin / 40% recycled	Landfill
iii	Compare raw materials	100% recycled	Landfill
iv	Baseline (end of life - EoL)	100% virgin	Landfill
v	Compare EoL	100% virgin	Incineration
vi	Compare EoL	100% virgin	Incineration with cogeneration of electricity
vii	Compare EoL	100% virgin	Recycling
viii*	Only to compare with MCI	100% recycled	Recycling

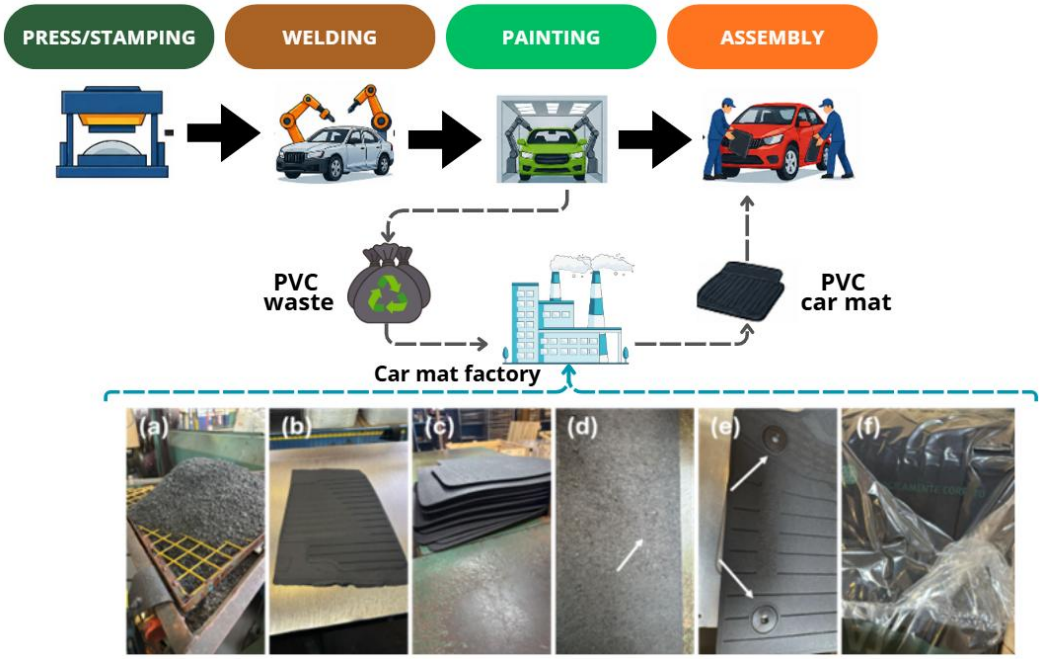
*Scenario viii was used only for the MCI calculation and was not included in the comparative LCA impact assessment.

Source: Authors.

The floor mat company, a large manufacturer with a diversified portfolio that supplies floor mats to several automakers, reported that the main source of PVC waste comes from PVC banners and tarpaulins. More recently, the company also began receiving PVC waste from some automakers that previously sent this material to co-processing, thereby enabling the closure of this PVC loop in the automobile production process (closed-loop circular economy) (Figure 2). The production of automotive

floor mats using recycled PVC involves the following steps: raw material receipt, (a) shredding of PVC waste, (b) extrusion of shredded PVC and molding, (c) trimming to ensure dimensional conformity, (d) insertion of a traceability code and (e) safety locks, and finally (f) inspection, packaging, and shipping. The floor mats are then delivered to customers, used, and discarded at the end of their life.

Fig. 2 PVC waste flow: OEM (original equipment manufacturer) → car floor mat manufacturer → OEM (closed-loop)



(a) Shredded PVC, (b) extruded floor mat before trimming, (c) floor mat after trimming, (d) floor mat with traceability code, (e) floor mat with safety locks, (f) packaged floor mat set

Source: Authors.

2.1.2 Life cycle inventory (LCI)

Primary data were collected from an automotive floor mat manufacturer, including detailed information on raw materials, other consumables, and transportation required for floor mat production. Secondary data were obtained from the Ecoinvent v3.10 library through OpenLCA v2.2. The detailed input table for floor mat production (Table 2) was structured to cover each of the proposed scenarios (see Table 1).

Table 2 LCI data

Item	Phase	Ecoinvent v3.10 (geographical scope)	Scenario								Unit
			(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)	
Virgin PVC	Raw material	polyvinylchloride production, suspension polymerisation (RoW*)	3.3	1.98	0	3.3	3.3	3.3	3.3	0	kg
Recycled PVC	Raw material	modeled from primary data from the floor mat factory (Brazil)	0	1.32	3.3	0	0	0	0	3.3	kg
PA66	Raw material	market for nylon 6-6 (RoW)	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	kg
Electricity	Production	market for electricity, medium voltage (BR-South-eastern/Mid-western grid)	1.842	2.15	2.602	1.842	1.842	1.842	1.842	2.602	kWh
Wooden packing	Packing	market for EUR-flat pallet | EUR-flat pallet (RoW)	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	kg
Paper packing	Packing	market for paper, woodcontaining, lightweight coated (RoW)	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	kg
Plastic packing	Packing	market for packaging film, low density polyethylene (GLO*)	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	kg
Floor sweepings	Industrial waste	treatment of municipal solid waste, sanitary landfill (RoW)	8E-04	8E-04	8E-04	8E-04	8E-04	8E-04	8E-04	8E-04	kg
Cleaning detergent	Use	soap production (RoW)	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	kg
Water	Use	market for tap water (Brazil)	60	60	60	60	60	60	60	60	kg
Wastewater treatment	Use	treatment of wastewater, average, wastewater treatment (RoW)	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	m3
Landfill	EoL	treatment of waste polyvinylchloride, sanitary landfill (RoW)	3.34	3.34	3.34	3.34	0	0	0	0	kg
Incineration	EoL	treatment of waste polyvinylchloride, municipal incineration (GLO)	0	0	0	0	3.34	3.34	0	0	kg
Cogeneration of electricity	EoL	market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - BR	0	0	0	0	0	-24	0	0	MJ

*RoW: Rest-of-world; GLO: Global. Source: Authors.

For the production of the automotive PVC floor mat set studied, 4.9 kg of PVC (virgin and/or recycled), two PA66 safety locks totaling 40 g, packaging materials (pallet, paper, and plastic film), electricity (Table S1, Supplementary Information), and the corresponding industrial waste are required. Although 4.9 kg of PVC enter the manufacturing process, 1.6 kg of PVC are cut during trimming to meet the dimensional standard. However, this waste returns to the production process as raw material for the next floor mat set. Therefore, 3.3 kg of PVC raw material was considered in the modeling.

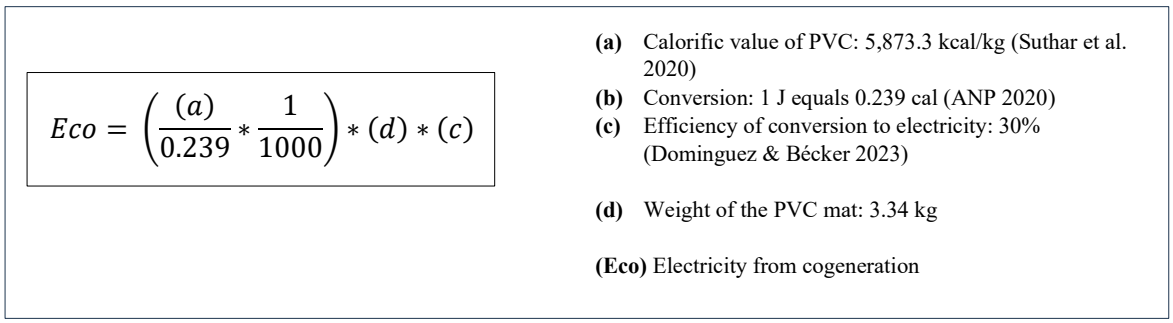
In scenarios (ii) and (iii), LCI modeling considered the use of PVC waste as part of the floor mat raw material. For this purpose, a mapping was conducted with the floor mat manufacturer to understand the steps required to recycle this material, as well as its main suppliers. It was found that recycling the

PVC waste received at the plant requires only grinding as an additional step. Therefore, a specific PVC dataset was created using the cut-off criterion.

Under this criterion, the environmental burden of extraction and production of the virgin raw material is assigned to the first cycle, while the subsequent cycle, which recycles the waste, receives the recycled raw material only with the environmental burden of the recycling process itself (Ekvall *et al.* 2020), in this case, waste grinding.

To model the incineration proposed in scenario (iv), a modeling assumption was adopted: the incineration process of 3.34 kg of floor mat at end of life (PVC floor mat waste) was considered to have the potential to contribute 24 MJ through electricity cogeneration, as detailed in Figure 3.

Fig. 3 Details of the modeling of incineration with cogeneration



Source: Authors.

Similarly to the assumptions adopted for energy cogeneration, assumptions were also adopted to enable modeling of the use phase of the automotive floor mat. A useful life of 2 years was considered for one floor mat set (Rajput *et al.* 2025), with six washings per year and an estimated consumption of five liters of water and 20 g of soap per washing (Cleanipedia 2026).

The modeling of transportation flows and distribution logistics was structured based on the actual supply and disposal locations (Table 3). For recycled PVC used as raw material, a weighted average of the main suppliers of this material to the company was used, based on the average sales volume of each supplier. The calculation of emissions and environmental impacts associated with these trips, as well as with secondary-data industrial processes, used the Ecoinvent v3.10 process "transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | Cutoff, U – BR", since all transportation is road-based and carried out by trucks.

Table 3 Transportation data used for LCA modeling

Scenario	Item	Percentage	Weight (kg)	Source	Distance (km)
i, iv, v, vi	Virgin PVC	100%	3.30	Supplier X	81
ii	Virgin PVC	60%	1.98	Supplier X	81
	PVC waste (*raw-material)*	13.2%	0.44	Supplier Y	424
		13.2%	0.44	Supplier Z	325
		13.2%	0.44	Supplier W	10
		0.4%	0.01	Supplier A	110
iii	PVC waste (*raw-material)*	33.0%	1.09	Supplier Y	424
		33.0%	1.09	Supplier Z	325
		33.0%	1.09	Supplier W	10
		1.00%	0.03	Supplier A	110
i, ii, iii, iv, v, vi	PA66	100%	0.04	Other supplier	80
i, ii, iii, iv, v, vi	Paper	100%	0.01	Other supplier	80
i, ii, iii, iv, v, vi	Plastic	100%	0.0027	Other supplier	80
i, ii, iii, iv, v, vi	Wood	100%	0.005	Other supplier	80
i, ii, iii, iv, v, vi	Floor sweepings	100%	0.0008	Case study industry	80
i, ii, iii, iv, v, vi	Finished product	100%	3.40	Case study industry	110
i, ii, iii, iv, v, vi	Waste Paper	100%	0.01	Case study industry	30
i, ii, iii, iv, v, vi	Waste Plastic	100%	0.0027	Case study industry	30
i, ii, iii, iv, v, vi	Waste Wood	100%	0.005	Case study industry	30
i, ii, iii, iv, v, vi	EoL car mat	100%	3.34	Case study industry	100

Source: Authors.

2.1.3 Impact assessment

The ReCiPe 2016 Midpoint (H) method was used to assess potential life cycle impacts, as it is commonly applied in LCA studies of polymers (Luo *et al*. 2024; Renkin and Limbourg 2025; Ye *et al*. 2017). Therefore, this method was selected to convert inventory data into 18 potential environmental impact categories through characterization factors.

The impact assessment included the following categories: terrestrial acidification (AT), climate change (CC), freshwater ecotoxicity (EF), marine ecotoxicity (EM), terrestrial ecotoxicity (ET), non-renewable fossil energy resources (ER), freshwater eutrophication (Eut. Fre.), marine eutrophication (Eut. Mar.), human toxicity: carcinogenic (HT-Car.), human toxicity: non-carcinogenic (HT-non-car.), ionising radiation (IR), land use (LU), material resources: metals/minerals (MR), ozone depletion (OD), particulate matter formation (PMF), photochemical oxidant formation: human health (POF-HH), photochemical oxidant formation: terrestrial ecosystems (POF-T), and water use (WU).

2.2 Material Circularity Indicator (MCI)

To assess the circularity of the PVC floor mat, the Material Circularity Indicator (MCI) was used for each proposed scenario. The MCI is considered a robust environmental indicator because it allows the inclusion of reuse parameters, recycled material content, recycling process efficiency, product lifetime, and product end of life within its scope of analysis (Martins *et al.* 2024). For this purpose, the tool indicated by the Ellen MacArthur Foundation (2026) and made available by Thinkstep-ANZ (2026) was used.

The MCI study was compared with the climate change (CC) category, considering that this impact category is widely discussed and studied, especially for fossil-based polymers.

3 Results and discussion

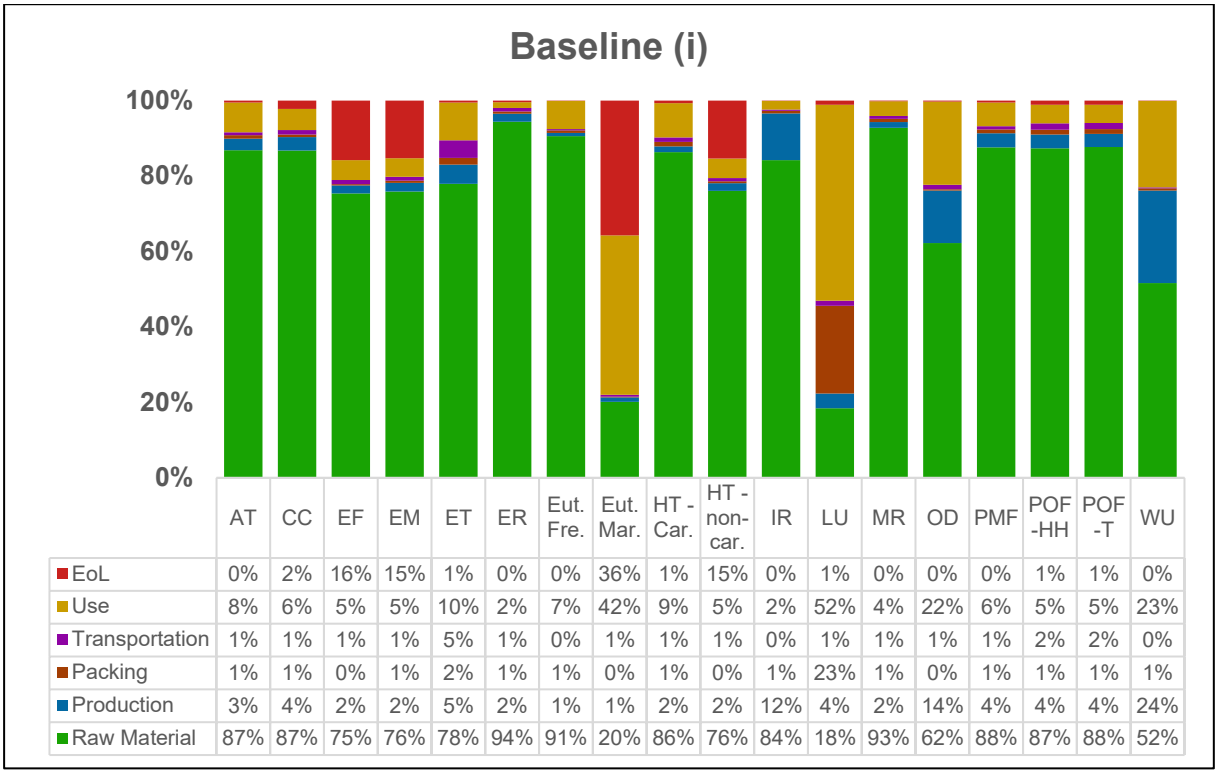
3.1 LCA results

This section presents the LCA results for the PVC floor mat, considering the seven proposed scenarios and the 18 impact categories of the LCIA method, to assess the influence of PVC raw material composition (Section 3.1.1) and the influence of the proposed EoL strategies (Section 3.1.2). To facilitate interpretation, the results were analyzed by life cycle stage: raw material (including extraction and production of raw materials), production (floor mat production stage using manufacturer foreground data), packaging (including all product packaging), transportation (including all transportation required in the life cycle of each scenario), use (including use and cleaning of the floor mat set), and EoL (including the different strategies for each scenario). The LCA results for each category in each scenario are available in Table S2 (Supplementary Information).

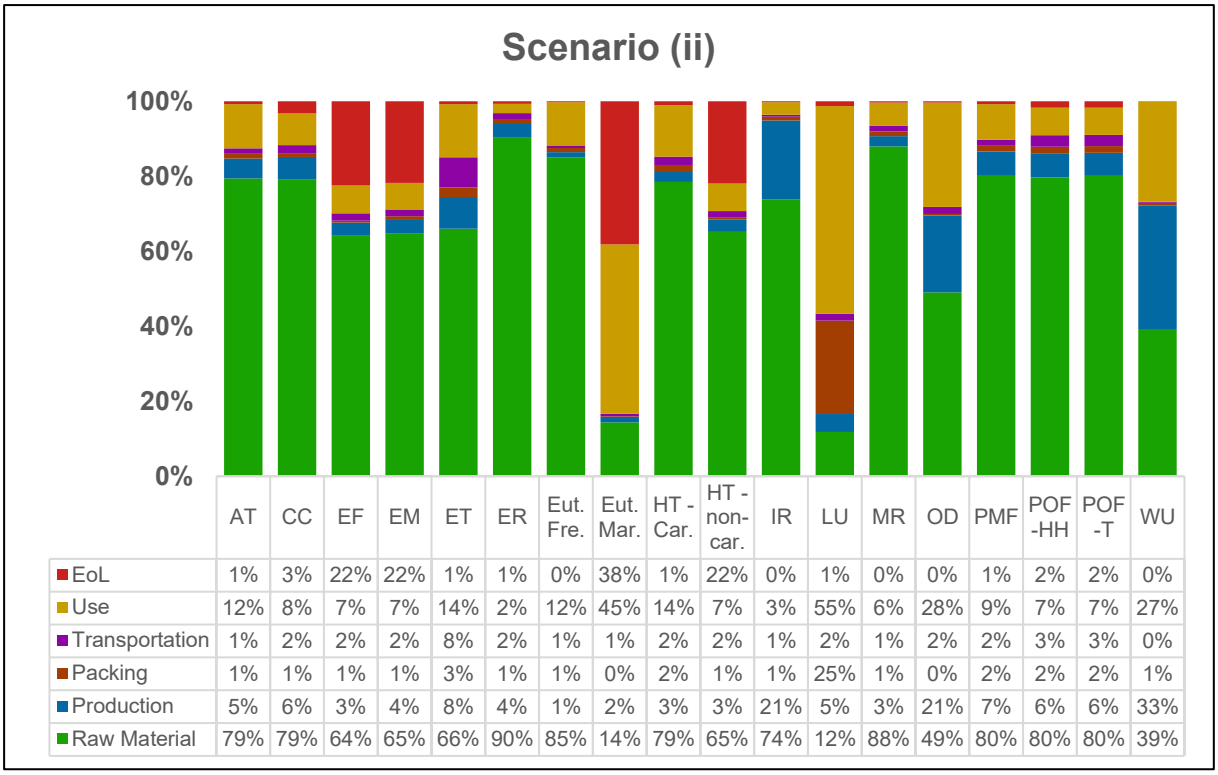
3.1.1 LCA results for raw material composition

The composition of the PVC studied, and the influence of recovered polymer incorporation rates were assessed for scenarios (i), (ii), and (iii), as shown in Figure 4.

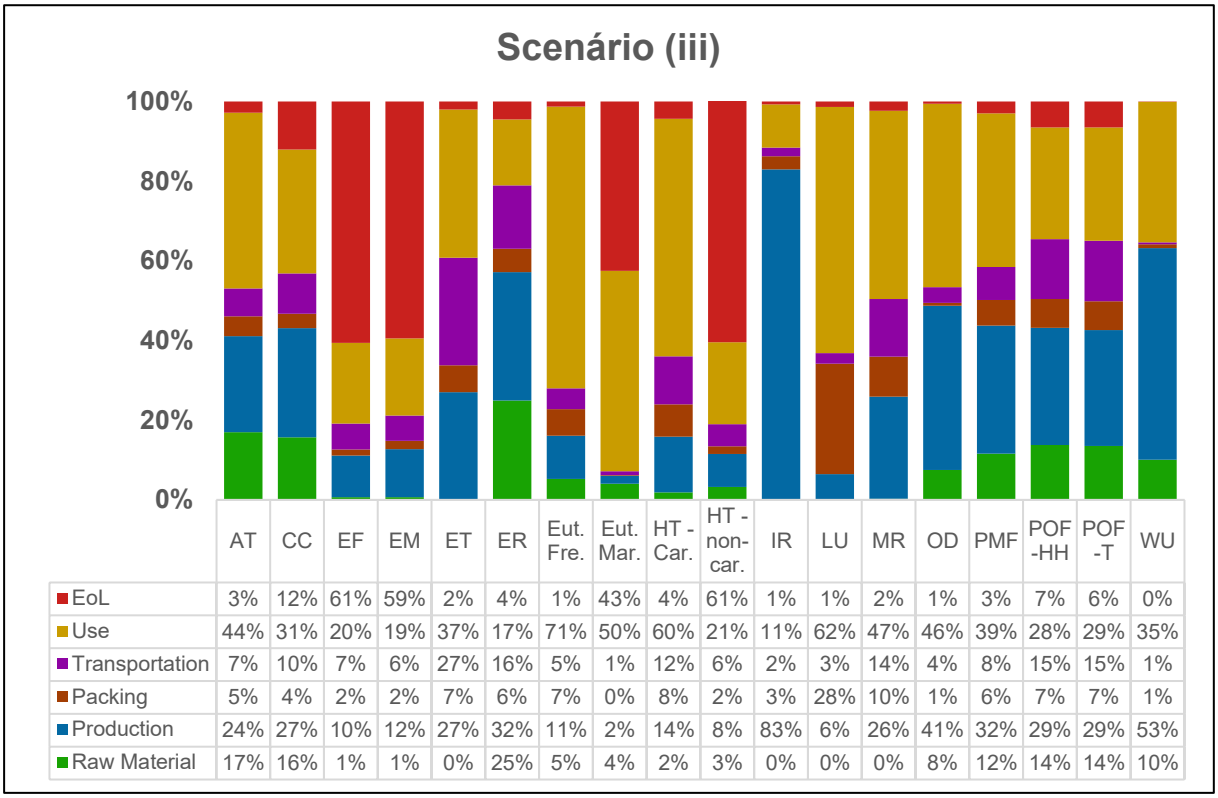
Fig. 4 Potential environmental impacts for the 18 ReCiPe categories in scenarios i, ii, and iii



	AT	CC	EF	EM	ET	ER	Eut. Fre.	Eut. Mar.	HT - Car.	HT - non-car.	IR	LU	MR	OD	PMF	POF -HH	POF -T	WU
EoL	0%	2%	16%	15%	1%	0%	0%	36%	1%	15%	0%	1%	0%	0%	0%	1%	1%	0%
Use	8%	6%	5%	5%	10%	2%	7%	42%	9%	5%	2%	52%	4%	22%	6%	5%	5%	23%
Transportation	1%	1%	1%	1%	5%	1%	0%	1%	1%	1%	0%	1%	1%	1%	1%	2%	2%	0%
Packing	1%	1%	0%	1%	2%	1%	1%	0%	1%	0%	1%	23%	1%	0%	1%	1%	1%	1%
Production	3%	4%	2%	2%	5%	2%	1%	1%	2%	2%	12%	4%	2%	14%	4%	4%	4%	24%
Raw Material	87%	87%	75%	76%	78%	94%	91%	20%	86%	76%	84%	18%	93%	62%	88%	87%	88%	52%



	AT	CC	EF	EM	ET	ER	Eut. Fre.	Eut. Mar.	HT - Car.	HT - non-car.	IR	LU	MR	OD	PMF	POF -HH	POF -T	WU
EoL	1%	3%	22%	22%	1%	1%	0%	38%	1%	22%	0%	1%	0%	0%	1%	2%	2%	0%
Use	12%	8%	7%	7%	14%	2%	12%	45%	14%	7%	3%	55%	6%	28%	9%	7%	7%	27%
Transportation	1%	2%	2%	2%	8%	2%	1%	1%	2%	2%	1%	2%	1%	2%	2%	3%	3%	0%
Packing	1%	1%	1%	1%	3%	1%	1%	0%	2%	1%	1%	25%	1%	0%	2%	2%	2%	1%
Production	5%	6%	3%	4%	8%	4%	1%	2%	3%	3%	21%	5%	3%	21%	7%	6%	6%	33%
Raw Material	79%	79%	64%	65%	66%	90%	85%	14%	79%	65%	74%	12%	88%	49%	80%	80%	80%	39%



	AT	CC	EF	EM	ET	ER	Eut. Fre.	Eut. Mar.	HT - Car.	HT - non-car.	IR	LU	MR	OD	PMF	POF -HH	POF -T	WU
EoL	3%	12%	61%	59%	2%	4%	1%	43%	4%	61%	1%	1%	2%	1%	3%	7%	6%	0%
Use	44%	31%	20%	19%	37%	17%	71%	50%	60%	21%	11%	62%	47%	46%	39%	28%	29%	35%
Transportation	7%	10%	7%	6%	27%	16%	5%	1%	12%	6%	2%	3%	14%	4%	8%	15%	15%	1%
Packing	5%	4%	2%	2%	7%	6%	7%	0%	8%	2%	3%	28%	10%	1%	6%	7%	7%	1%
Production	24%	27%	10%	12%	27%	32%	11%	2%	14%	8%	83%	6%	26%	41%	32%	29%	29%	53%
Raw Material	17%	16%	1%	1%	0%	25%	5%	4%	2%	3%	0%	0%	0%	8%	12%	14%	14%	10%

Source: Authors.

Overall, similar behavior was observed across the impact categories for scenarios (i) and (ii), because both scenarios use virgin PVC, corresponding to 100% and 60% of the floor mat composition, respectively. In these scenarios, the raw material extraction and production stage represented the hotspot in almost all categories (16/18): AT, CC, EF, EM, ET, ER, Eut. Fre., HT-Car., HT-non-car., IR, MR, OD, PMF, POF-HH, POF-T, and WU. Only for marine eutrophication (Eut. Mar.) and land use (LU) was a different hotspot identified, located in the floor mat use phase.

This result indicates the need for attention to the product use phase, since the small amount of water and soap used for periodic cleaning generated significant contributions to marine eutrophication and land use. In this sense, future research could include sensitivity studies with different detergent options to assess the behavior of these potential impacts.

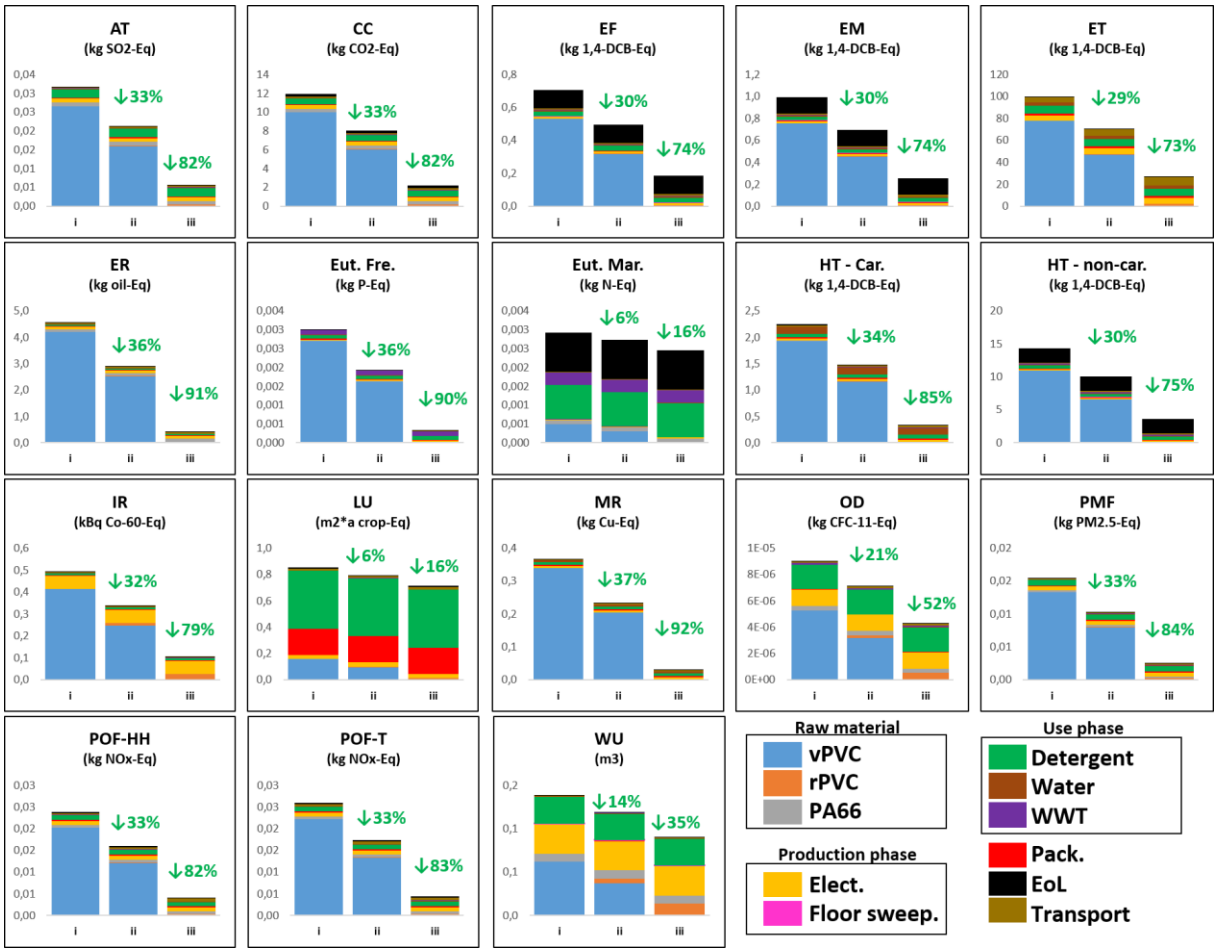
Although the consumption of virgin material (PVC) decreased to 60% of the product from scenario (i) to scenario (ii), the hotspot persisted in the raw material extraction and production stage for most impact categories (16/18). The MR category deserves emphasis, as virgin PVC acquisition (88%) and recycled PVC (0.5%) showed high contributions.

When compared with scenario (iii), in which the product is composed of 100% recycled material, a marked change in the behavior of the impact categories can be observed. With the production of the PVC floor mat using 100% recycled raw material, the raw material extraction and production stage ceased to be the hotspot in almost all categories, as observed in scenarios (i) and (ii). Among the 18 categories assessed, ten categories (AT, CC, ET, Eut. Fre., Eut. Mar., HT-Car., LU, MR, OD, and PMF) had the use phase as the hotspot; five categories (ER, IR, POF-HH, POF-T, and WU) had the production phase, that is, the floor mat manufacturing steps themselves, as the hotspot; and three

categories (EF, EM, and HT-non-car.) presented the main impacts for the EoL strategies. This scenario highlights that the use of recycled PVC contributes to reducing the potential life cycle impacts of the floor mat (Supplementary Table S2), emphasizing the relevance of circular economy and recycled material use.

To verify the divergence in absolute terms among the different scenarios, a graph (Figure 5) was plotted with the impact values obtained for each life cycle process. From left to right, the first column refers to the scenario using 100% virgin material (i), the middle column to the scenario using 40% recycled material (ii), and the right column to the scenario in which the floor mat is produced with 100% recycled PVC (iii). In addition, the percentage variation in impact of a given scenario relative to the baseline scenario can be assessed, shown in green with a downward arrow indicating impact reduction. Figure 5 shows the individual contribution, in terms of potential impact, of each item that composes the product system according to each scenario (Table 1) throughout the life cycle: vPVC (virgin PVC), rPVC (recycled PVC), and PA66 (polyamide 66) as raw material items; Elect. (use of electricity in the car mat production phase) and Floor sweep. (waste generated in the car mat production phase) during the floor mat production phase; Pack. (packaging used); Transport (logistics involved throughout the life cycle); detergent and water (used in the use phase), WWT (wastewater treatment, treatment of the effluent generated during use); and EoL (end of life).

Fig. 5 Potential absolute environmental impacts for the 18 categories of ReCiPe for the scenarios i, ii and iii



Source: Authors.

The absolute results show a significant decrease in impacts for the scenarios using fully recycled PVC (iii) and partially recycled PVC (ii) when compared with the baseline scenario (i), which uses 100% virgin material.

Scenario (ii), when compared with the baseline scenario (i), showed a reduction in contribution results ranging from 6% to 37%, with emphasis on the MR, ER, Eut. Fre., and HT-Car. categories, which decreased by 37%, 36%, 36%, and 34%, respectively. Similarly, when the scenario using 100% recycled PVC (iii) was compared with the baseline scenario (i), an even more evident potential reduction in impacts was identified, ranging from 16% to 92%. The MR, ER, Eut. Fre., and HT-Car. categories also stood out, with reductions of 92%, 91%, 90%, and 85%, respectively.

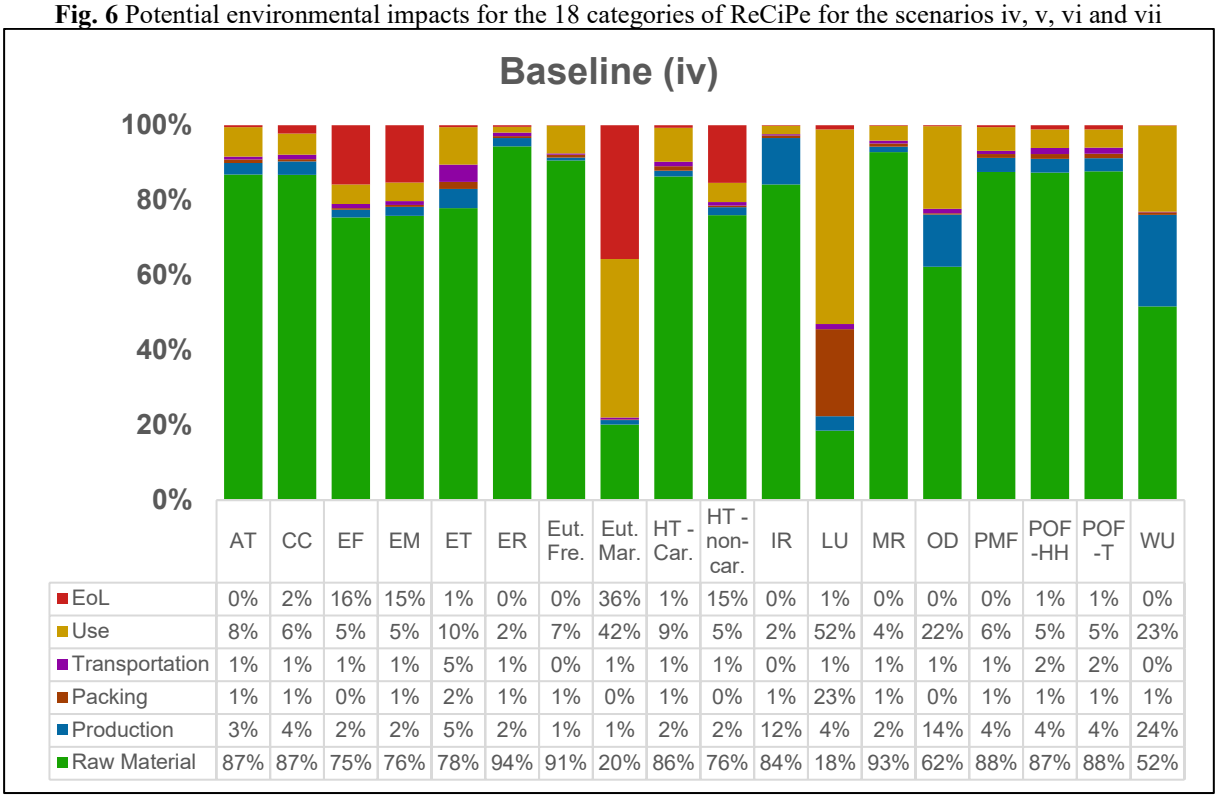
The behavior described above confirms the initial hypotheses that using recycled material is essential not only to close material loops and make the production process more circular, but also to reduce potential environmental impacts, ranging from climate change (in kg CO2 equivalent) to human toxicity impacts (in kg 1,4-dichlorobenzene equivalent).

In addition to the absolute reduction already highlighted, Figure 5 also shows a change in the contribution profile among scenarios: as the rPVC fraction increases, impacts become less concentrated in the virgin raw material stage and become relatively more distributed across other system processes, such as transportation, electricity use, packaging, cleaning, and end of life. This indicates that replacing vPVC with rPVC not only reduces total impacts, but also shifts the main environmental hotspots to auxiliary life cycle stages, which should receive greater attention in future system optimization strategies.

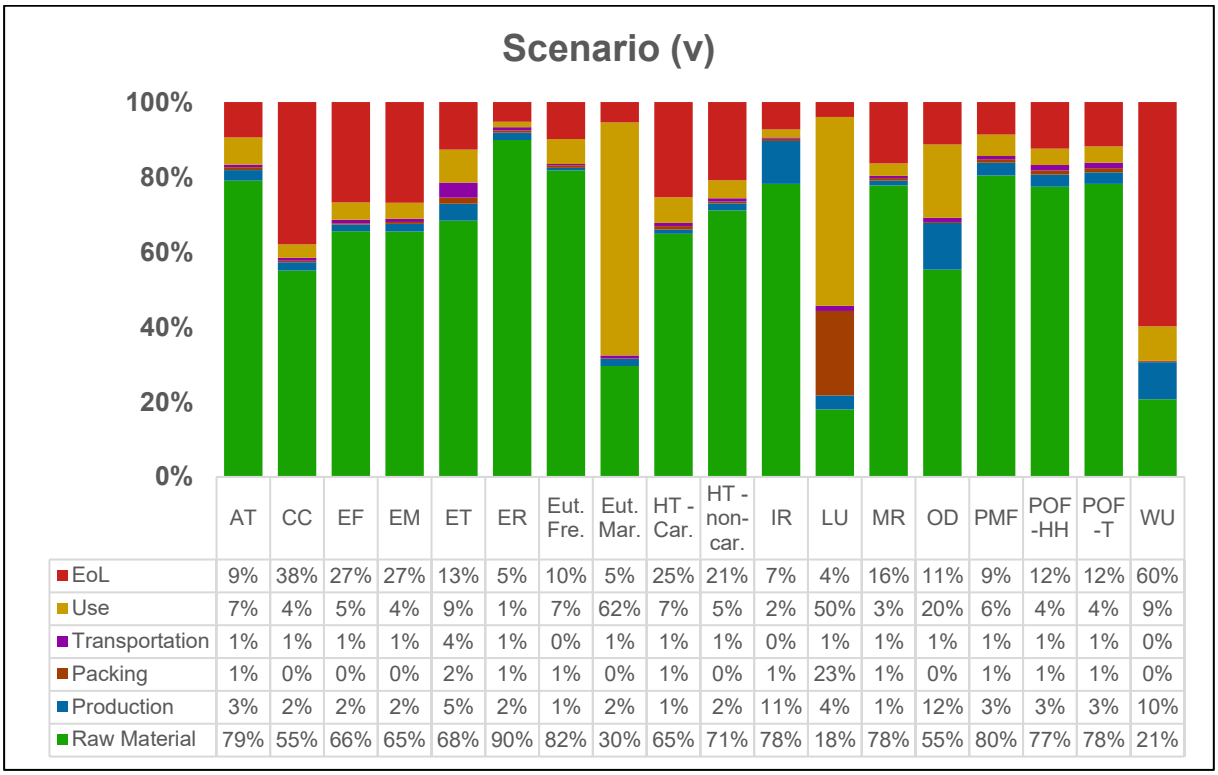
3.1.2 LCA results for EoL strategies

Similarly to the analysis conducted for scenarios (i), (ii), and (iii), in which raw material composition varies, the results for scenarios with 100% virgin PVC and variation in EoL strategies, ranging from landfill (iv), incineration (v), incineration with cogeneration (vi), and recycling (vii), were analyzed in normalized form (Figure 6) and in absolute terms (Figure 7).

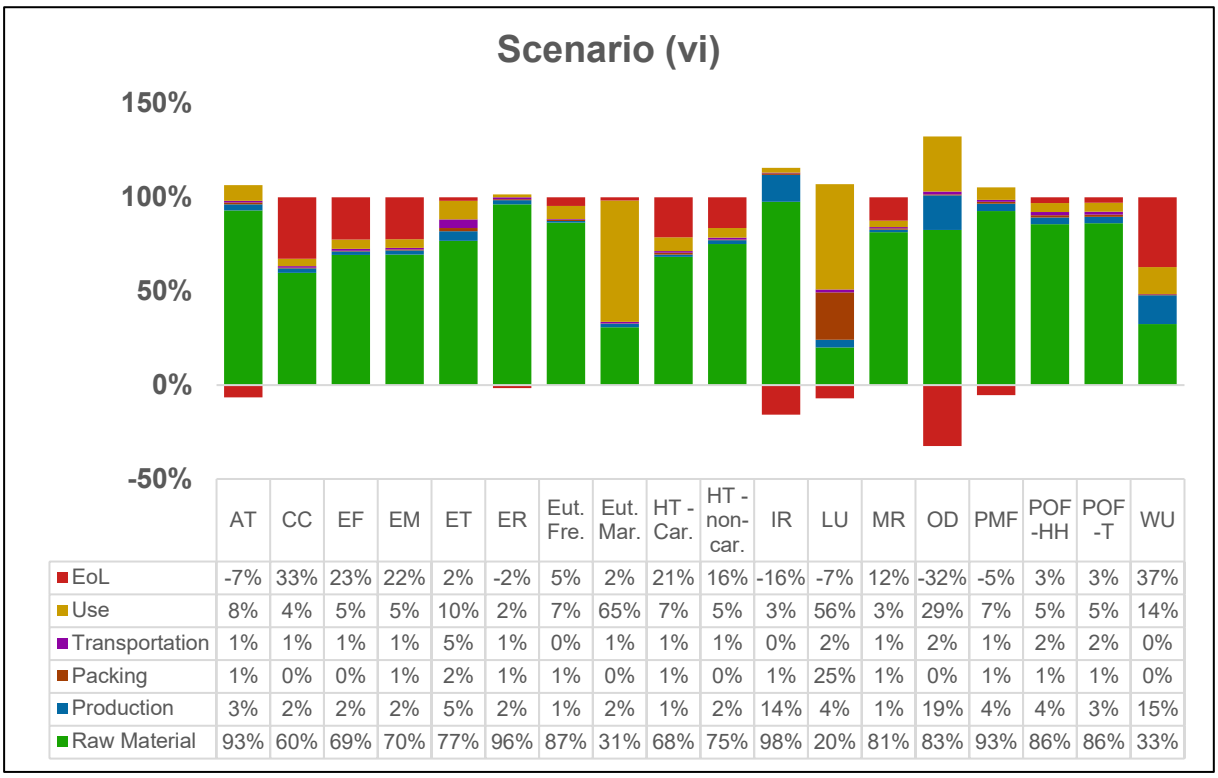
Fig. 6 Potential environmental impacts for the 18 categories of ReCiPe for the scenarios iv, v, vi and vii



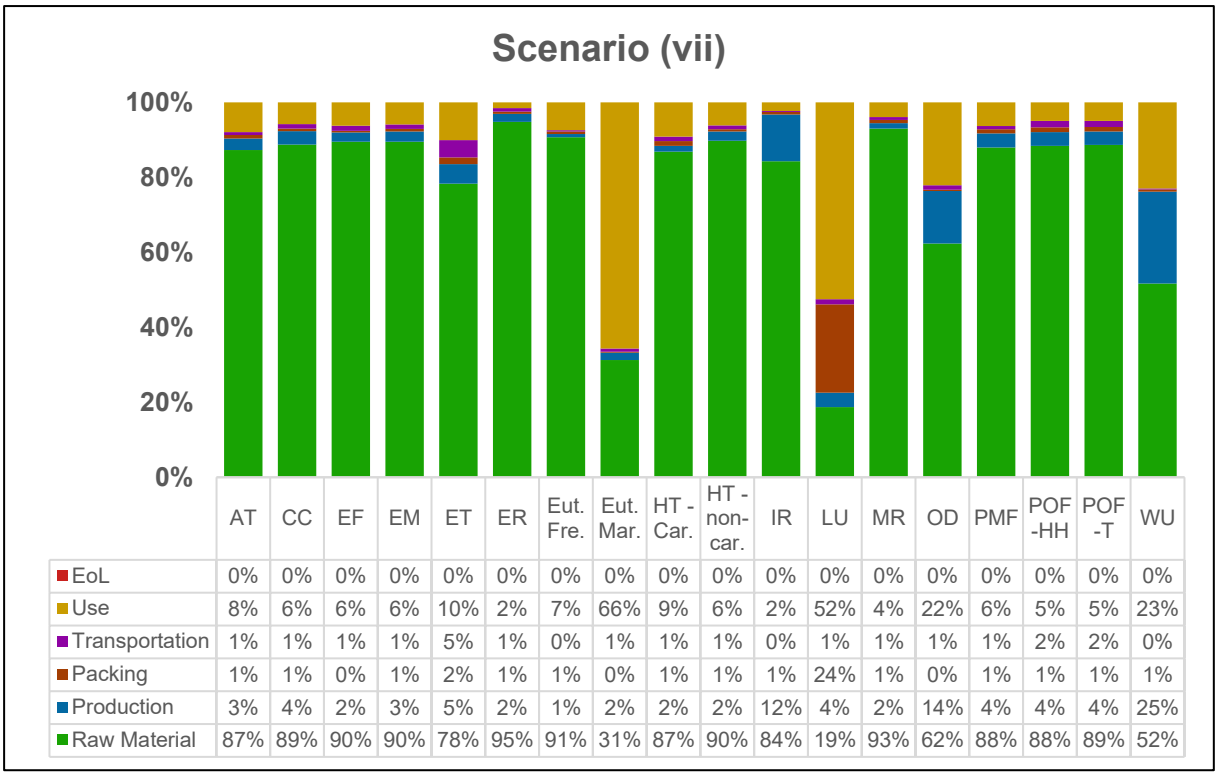
	AT	CC	EF	EM	ET	ER	Eut. Fre.	Eut. Mar.	HT - Car.	HT - non-car.	IR	LU	MR	OD	PMF	POF -HH	POF -T	WU
EoL	0%	2%	16%	15%	1%	0%	0%	36%	1%	15%	0%	1%	0%	0%	0%	1%	1%	0%
Use	8%	6%	5%	5%	10%	2%	7%	42%	9%	5%	2%	52%	4%	22%	6%	5%	5%	23%
Transportation	1%	1%	1%	1%	5%	1%	0%	1%	1%	1%	0%	1%	1%	1%	1%	2%	2%	0%
Packing	1%	1%	0%	1%	2%	1%	1%	0%	1%	0%	1%	23%	1%	0%	1%	1%	1%	1%
Production	3%	4%	2%	2%	5%	2%	1%	1%	2%	2%	12%	4%	2%	14%	4%	4%	4%	24%
Raw Material	87%	87%	75%	76%	78%	94%	91%	20%	86%	76%	84%	18%	93%	62%	88%	87%	88%	52%



	AT	CC	EF	EM	ET	ER	Eut. Fre.	Eut. Mar.	HT - Car.	HT - non-car.	IR	LU	MR	OD	PMF	POF -HH	POF -T	WU
EoL	9%	38%	27%	27%	13%	5%	10%	5%	25%	21%	7%	4%	16%	11%	9%	12%	12%	60%
Use	7%	4%	5%	4%	9%	1%	7%	62%	7%	5%	2%	50%	3%	20%	6%	4%	4%	9%
Transportation	1%	1%	1%	1%	4%	1%	0%	1%	1%	1%	0%	1%	1%	1%	1%	1%	1%	0%
Packing	1%	0%	0%	0%	2%	1%	1%	0%	1%	0%	1%	23%	1%	0%	1%	1%	1%	0%
Production	3%	2%	2%	2%	5%	2%	1%	2%	1%	2%	11%	4%	1%	12%	3%	3%	3%	10%
Raw Material	79%	55%	66%	65%	68%	90%	82%	30%	65%	71%	78%	18%	78%	55%	80%	77%	78%	21%



	AT	CC	EF	EM	ET	ER	Eut. Fre.	Eut. Mar.	HT - Car.	HT - non-car.	IR	LU	MR	OD	PMF	POF -HH	POF -T	WU
EoL	-7%	33%	23%	22%	2%	-2%	5%	2%	21%	16%	-16%	-7%	12%	-32%	-5%	3%	3%	37%
Use	8%	4%	5%	5%	10%	2%	7%	65%	7%	5%	3%	56%	3%	29%	7%	5%	5%	14%
Transportation	1%	1%	1%	1%	5%	1%	0%	1%	1%	1%	0%	2%	1%	2%	1%	2%	2%	0%
Packing	1%	0%	0%	1%	2%	1%	1%	0%	1%	0%	1%	25%	1%	0%	1%	1%	1%	0%
Production	3%	2%	2%	2%	5%	2%	1%	2%	1%	2%	14%	4%	1%	19%	4%	4%	3%	15%
Raw Material	93%	60%	69%	70%	77%	96%	87%	31%	68%	75%	98%	20%	81%	83%	93%	86%	86%	33%



	AT	CC	EF	EM	ET	ER	Eut. Fre.	Eut. Mar.	HT - Car.	HT - non-car.	IR	LU	MR	OD	PMF	POF -HH	POF -T	WU
EoL	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Use	8%	6%	6%	6%	10%	2%	7%	66%	9%	6%	2%	52%	4%	22%	6%	5%	5%	23%
Transportation	1%	1%	1%	1%	5%	1%	0%	1%	1%	1%	0%	1%	1%	1%	1%	2%	2%	0%
Packing	1%	1%	0%	1%	2%	1%	1%	0%	1%	1%	1%	24%	1%	0%	1%	1%	1%	1%
Production	3%	4%	2%	3%	5%	2%	1%	2%	2%	2%	12%	4%	2%	14%	4%	4%	4%	25%
Raw Material	87%	89%	90%	90%	78%	95%	91%	31%	87%	90%	84%	19%	93%	62%	88%	88%	89%	52%

Source: Authors.

Similar to what occurred in scenarios (i) and (ii), in scenarios (iv), (v), (vi), and (vii), the potential impact of the raw material extraction and production phase was predominant in most categories (15/18), regardless of the EoL strategy adopted. This condition was evident for AT, CC, EF, EM, ET, ER, Eut. Fre., HT-Car., HT-non-car., IR, MR, OD, PMF, POF-HH, and POF-T.

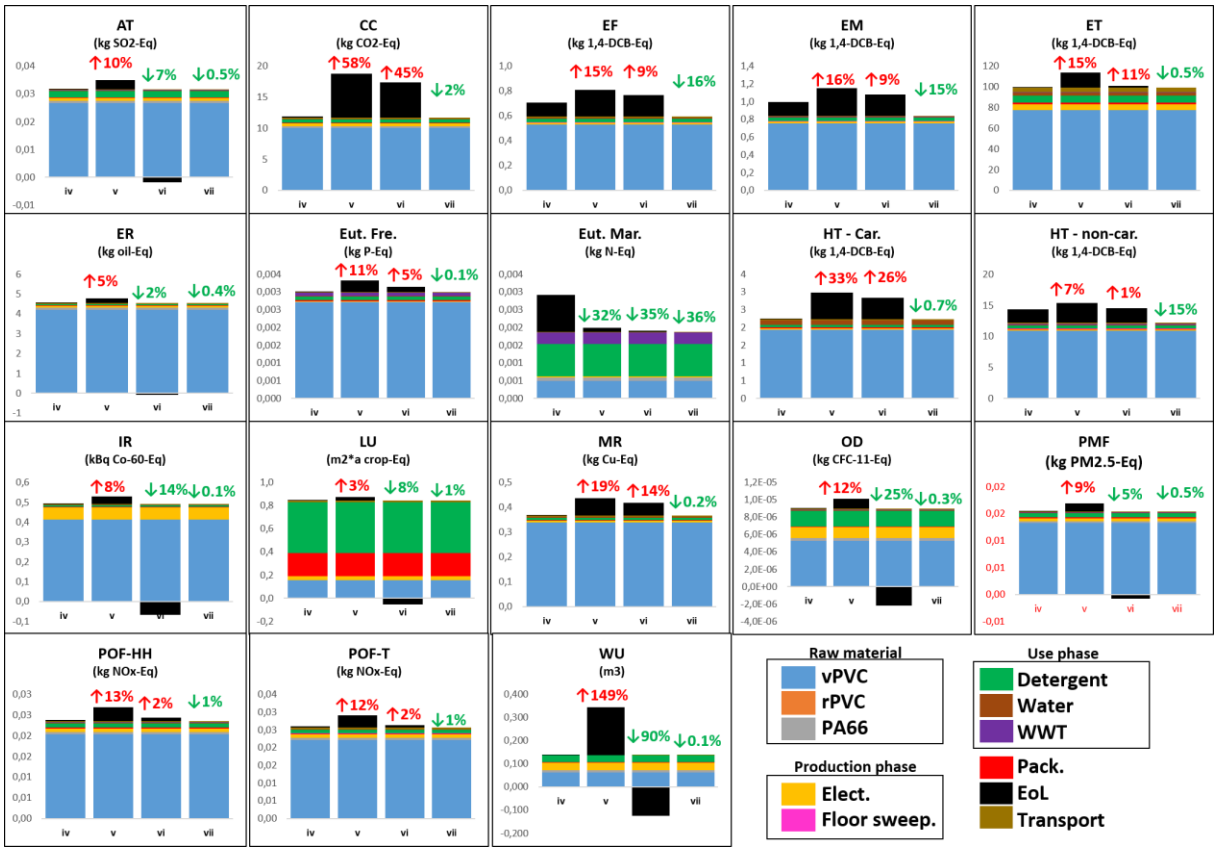
On the other hand, the marine eutrophication (Eut. Mar.) and land use (LU) categories, regardless of the EoL modeling adopted, showed the highest potential impact in the use phase, as also observed for scenarios (i), (ii), and (iii). The Eut. Mar. category in the incineration scenario (v) deserves emphasis, as detergent use (45%) and water use (17%) for cleaning represented high contribution percentages.

For the water use (WU) impact category, in the landfill (iv) and recycling (vii) scenarios, the potential impact was concentrated in the raw material extraction and production phase, totaling 52% of impacts in both scenarios. For the models considering incineration (v) and incineration with electricity cogeneration (vi) as EoL strategies, the main potential impact was attributed to the EoL phase itself, with contributions of 60% and 37%, respectively.

In the incineration with electricity cogeneration scenario (vi), impact categories with negative values for the EoL phase were clearly observed, namely AT, ER, IR, LU, OD, and PMF. This occurred because cogeneration helps reduce the potential impact, especially through the potential production of electricity from the end-of-life floor mat.

To simulate the use of 100% virgin PVC raw material and assess the EoL strategies in absolute terms, namely landfill (iv), incineration (v), incineration with electricity cogeneration (vi), and recycling (vii), the graph in Figure 7 was plotted. The percentage variation shown in red indicates that the compared impact potential increased relative to the absolute value observed for the baseline scenario (iv).

Fig. 7 Potential absolute environmental impacts for the scenarios iv, v, vi and vii



Source: Authors.

Comparing the incineration strategy (v) with landfill (iv), incineration increased the life cycle impact in almost all categories, with potential reduction only in the marine eutrophication (Eut. Mar.) category. In this case, incineration led to impact variations ranging from -32% to 149%; thus, scenario (v) could reduce impacts by up to 32%, as in the Eut. Mar. category, or increase them by up to 149%, as observed in the water use (WU) category.

In the comparison between incineration with energy cogeneration (vi) and landfill (iv), incineration showed lower potential impact for some categories (AT, ER, Eut. Mar., IR, LU, OD, PMF, and WU) and higher potential impact for others (CC, EF, EM, ET, Eut. Fre., HT-Car., HT-non-car., MR, POF-HH, and POF-T). In this comparison, no clear pattern was observed to define whether incineration with energy cogeneration is better or worse than landfill, given the observed variation.

For some categories, incineration with cogeneration (vi) increased potential impacts by between 1% and 45%, corresponding to human toxicity: non-carcinogenic (HT-non-car.) and climate change (CC), respectively. For other categories, it reduced impacts by between 2% and 90%, corresponding to non-renewable fossil energy resources (ER) and water use (WU), respectively. This aspect confirmed what was observed by Yun *et al.* (2025) in the study on a PVC recycling route linked to bioethanol production.

Similarly, Wu *et al.* (2014) compared the end of life of PVC waste through vacuum pyrolysis and incineration, both with energy cogeneration. Overall, the authors identified incineration as the most efficient strategy in energy terms, but with a higher potential environmental impact burden than pyrolysis (Wu *et al.* 2014).

When the recycling scenario (vii) was compared with landfill (iv), the results showed a potential impact reduction for recycling in all categories, with reductions ranging from 0.1% to 36% for water use (WU) and marine eutrophication (Eut. Mar.), respectively. As detailed in the methodology, the present study adopted the cut-off, or polluter-pays, criterion for LCA modeling. Therefore, for the recycling scenario (vii), only the impact of transporting PVC floor mat waste to the recycler was considered. The impacts associated with the recycling process itself and the benefit, or credit, from using recycled raw material were allocated to the subsequent cycle of recycled raw material use, as discussed in scenarios (ii) and (iii).

Finally, the comparative results for scenarios (iv), (v), (vi), and (vii) showed that incineration without energy cogeneration has the highest potential environmental impact when compared with the other EoL strategies, namely landfill disposal and incineration with energy cogeneration, which is currently still uncommon in Brazil (Ferraz de Campos *et al.* 2021).

3.1.3 Comparison of LCA results with the literature

According to the literature analyzed, relatively few LCA studies on automotive floor mats were found, with emphasis on the study by Örücü and Atilgan Türkmen (2022), which used a cradle-to-gate boundary and a Turkish scope. The authors indicated that the critical impact phase is concentrated in the

floor mat manufacturing stage, rather than in the extraction and production of raw materials (Örücü and Atilgan Türkmen 2022).

This dynamic reported by the authors differs somewhat from the results obtained in the present study. This divergence is due to the fact that the authors used natural rubber as the main input, whose upstream environmental footprint is lower than that of fossil-based polymer extraction and synthesis, namely virgin PVC in the present study.

Thus, the results of the present study showed that the extraction and production of virgin PVC constitute the main environmental hotspot of the product system. This behavior is supported by several previous studies (An *et al.* 2022; Bottausci *et al.* 2021; Liang *et al.* 2023; Stichnothe and Azapagic 2013; Ye *et al.* 2017). Likewise, a linear reduction in the impact potentials of all ReCiPe method categories was observed as the incorporation rate of recycled raw material increased (scenarios ii and iii). This observation reinforces the need to extend the life cycle of PVC polymers, especially through the use of recycled materials, directly converging with the circular economy findings discussed by Liang *et al.* (2023) and Stichnothe and Azapagic (2013).

Although the literature does not present cases of recycling and reinsertion of PVC waste directly linked to the automotive chain, the environmental feasibility of mechanical and chemical PVC recycling is widely suggested in other industrial sectors, especially in construction, as highlighted by Fakhri *et al.* (2023), Guzmán *et al.* (2024), Manjunatha *et al.* (2022, 2023), and Stichnothe and Azapagic (2013).

For example, when analyzing PVC reuse in flexible and related materials, Cholake *et al.* (2018) identified a 78% reduction in the climate change category compared with the use of virgin resin. Similar behavior was obtained in the present study, which achieved an 82% reduction in CC impacts when using 100% recycled PVC in the floor mat composition (scenario iii).

At the macrostructural level, Liang *et al.* (2023) demonstrated that circular strategies applied to the plastics chain in China, including PVC flows, can significantly reduce greenhouse gas (GHG) emissions and energy demand by replacing primary production with recycled products. Finally, the closed-loop assessment conducted by Stichnothe and Azapagic (2013) for PVC window frames confirmed that recycling and reinserting the material into the same process can minimize GHG emissions and primary energy consumption compared with the use of virgin polymer.

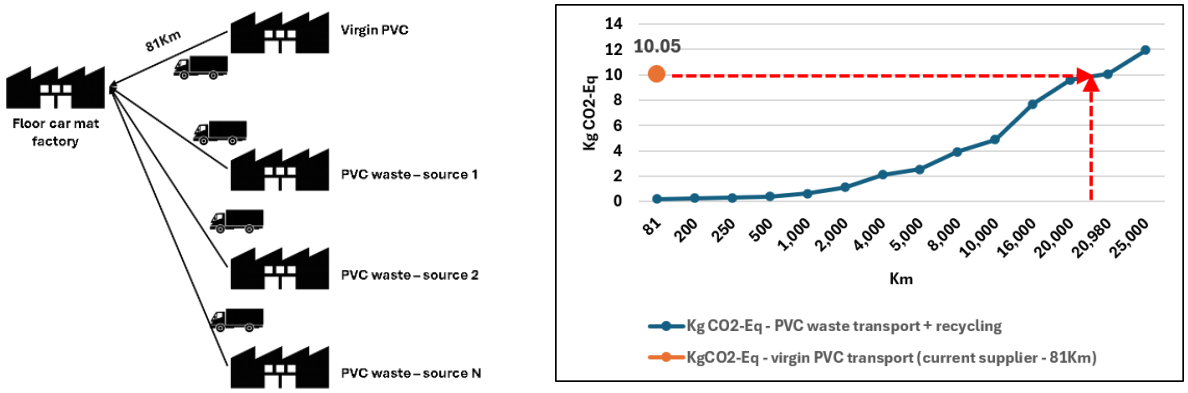
3.2 Sensitivity analysis for Transportation

Considering the potential environmental benefit of using recycled PVC raw material in scenarios (ii) and (iii), a sensitivity analysis was conducted on the logistical requirements for transporting recycled material to the floor mat manufacturing plant gate. For this purpose, the scenario considering 100% recycled PVC (iii) was assessed, in terms of climate change (kg CO2 equivalent), against the distance traveled by recyclers and recycling stages, in order to determine up to what distance it would be environmentally beneficial to transport PVC waste to the floor mat plant compared with the use of virgin PVC, scenario (i).

For this sensitivity analysis, the LCA modeling considered the following criteria: 3.3 kg of PVC (virgin or recycled); virgin PVC transported over a distance of 81 km, corresponding to the current PVC

supplier; and PVC waste transportation from its origin to the floor mat plant, including the electricity consumption for shredding/recycling the PVC waste. Different distances were considered for the sensitivity analysis, as shown in Figure 8.

Fig. 8 Sensitivity analysis for transportation in the climate change category



Source: Authors.

Overall, the potential impact of virgin PVC in terms of climate change showed a contribution of 10.05 kg CO2-eq, considering transportation over 81 km from the supplier to the focal company of the study. When assessing the scenario using 100% recycled PVC in the floor mat composition, it was evident that PVC waste, even when transported over 20,800 km, would still provide a benefit, in terms of kg CO2 equivalent, compared with the use of 100% virgin PVC. A similar result was observed in a recent study on the recycling of plastics from waste electrical and electronic equipment in Brazil, in which increased transportation distance for material recycling also had a relatively limited effect on total environmental impacts (da Silva *et al.* 2026).

3.3 MCI results

After the LCA, the MCI circularity indicator was calculated for the eight scenarios studied to assess their alignment with CE practices. For this purpose, the MCI results were compared with the climate change (CC) environmental impact category, measured in kg CO2 equivalent.

Similarly to the LCA application, it was necessary to define the inputs to be assessed in the MCI, that is, the parameters used to fill in the calculator for each scenario, such as the amount of recycled material, source, and EoL strategies adopted, as shown in Table 4.

Table 4 Comparison between MCI and LCA

Scenario	MCI Variables					
	PVC (kg)	PVC - source	PA66 (kg)	PA66 - source	End of life	Recycling efficiency
i	3.30	100% virgin	0.04	100% virgin	Landfill	NA***
ii	3.30	60% virgin, 40% recycled	0.04	100% virgin	Landfill	NA***
iii	3.30	100% recycled	0.04	100% virgin	Landfill	NA***
iv	3.30	100% virgin	0.04	100% virgin	Landfill	NA***
v	3.30	100% virgin	0.04	100% virgin	Incineration*	NA***
vi	3.30	100% virgin	0.04	100% virgin	Incineration with electricity cogeneration**	NA***
vii	3.30	100% virgin	0.04	100% virgin	Recycling	100%
viii	3.30	100% recycled	0.04	100% virgin	Recycling	100%

* In the MCI calculator, the "landfill" parameter was used because the "incineration" parameter was not available

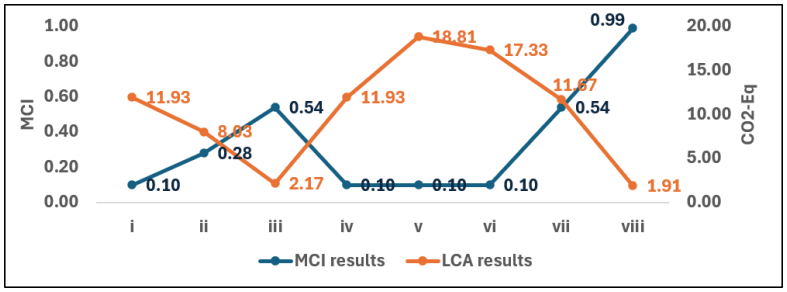
** In the MCI calculator, the "energy recovery" parameter was used because the "incineration with energy cogeneration" parameter was not available

*** NA – not applicable

Source: Authors.

After applying the MCI calculator (Thinkstep-ANZ 2026) (available at https://www.thinkstep-anz.com/services/circular-economy/material-circularity-indicator-mci-calculator/mci-trial), it was possible to compare the circularity results generated by the calculator with the potential greenhouse gas emission result for the climate change (CC) category obtained in the LCA, as shown in Figure 9.

Fig. 9 Comparison of MCI results and the climate change (CC) category of the LCA



Source: Authors.

Scenarios (i), (iv), (v), and (vi), despite varying in the CC category (LCA results), with climate change emission potentials of 11.93, 11.93, 18.81, and 17.33 kg CO2-eq, respectively, obtained the same MCI circularity indicator result of 0.1. This occurred because all these scenarios used virgin PVC raw material, varying only in the EoL strategies.

The use of virgin PVC associated with incineration (v) resulted in the most impactful scenario in terms of the climate change category and also presented the worst circularity index, together with scenarios (i), (iv), and (v).

Scenario (ii), composed of 40% recycled PVC and landfill as the EoL strategy, had an MCI of 0.28 and a CC potential of 8.03 kg CO2-eq, characterizing it as an intermediate scenario. The incorporation of 40% recycled PVC enables both an increase in MCI and a reduction in potential climate change impacts.

Scenarios (iii), 100% recycled PVC and landfill as EoL, and (vii), 100% virgin PVC and recycling as EoL, both presented an MCI result of 0.54, while their potential CC emissions were 2.17 and 11.76 kg CO2-eq, respectively. These results confirm the importance of evaluating MCI in association with LCA because, although both scenarios presented the same circularity indicator result, scenario (iii), with 100% recycled raw material, had an environmental impact potential 81% lower than scenario (vii) for the CC category. Therefore, using a judgment based only on the MCI circularity index, as demonstrated, could lead to an incorrect decision regarding potential environmental benefit.

Finally, for scenario viii (100% recycled PVC and recycling at end of life), the MCI result was 0.99 and the CC emission potential was 1.91 kg CO2-eq, reinforcing that integrating recycling at the end of the floor mat life cycle, thereby closing the loop, enables an index very close to full circularity (MCI value of 1).

Overall, the results reinforce the importance of pursuing material circularity, especially to reduce potential environmental impacts. In addition, they highlight the importance of jointly assessing LCA and MCI indicators to make circularity analyses more complete and to avoid the risk of premature decision-making. According to Martins *et al.* (2024), the MCI makes it possible to consider material origin, life cycle extension, and EoL strategies, while LCA enables a more holistic approach, especially because it can include transportation, the value chain, and other production processes involved in the product life cycle from an environmental assessment perspective.

4 Conclusions

The general objective of this study was to conduct a primary-data-based LCA case study applied to the incorporation of PVC waste in the industrial-scale production of PVC automotive floor mats. For this purpose, an LCA based on primary data was performed to analyze the environmental feasibility of incorporating polyvinyl chloride (PVC) waste into the industrial manufacture of automotive floor mats. In parallel, the scenarios were assessed from the perspective of the Material Circularity Indicator (MCI).

In addition, based on the literature reviewed, a knowledge gap was identified regarding the reuse of PVC in this segment, since previous studies have focused mainly on the construction sector.

Overall, the ecological feasibility of changing the floor mat composition was demonstrated through LCA. In the scenarios using only virgin PVC, the PVC extraction and production stage was identified as the most critical hotspot. However, the sensitivity analysis showed that the gradual replacement of virgin polymer with recycled material can reduce potential impacts in practically all evaluated categories.

The study also demonstrated the importance of associating the MCI circularity index with LCA for a more complete and accurate environmental assessment. This is because the combined analysis of

these tools allows not only the assessment of circularity potential to support decision-making, but also the holistic measurement of its associated potential environmental impacts. Finally, recycling was validated as the most eco-efficient EoL strategy, since it enables closed-loop management in the automotive chain while also reducing the associated potential impacts.

Overall, this research contributes to the circular economy in the automotive sector by highlighting the current state of the topic in the Brazilian context. The results obtained are directly aligned with the regulatory premises of the Green Mobility and Innovation Program (MOVER), providing decision-support information for industrial managers and public policymakers.

As limitations inherent to the scope, it is worth highlighting the restriction of the sample to a single company, the use of secondary data from the Ecoinvent v3.10 library, and the exclusion of economic and social dimensions from the analyses. For future developments, inventory updates, the integration of life cycle costing (LCC), expansion of the study boundary to other polymeric components in the sector, and a more in-depth sensitivity analysis for the use phase are recommended, since this varies according to consumer profiles.

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Declarations

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