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Environmental impact of three different engineering thermoplastics: How much does it change when using recycled polyamide?

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ABSTRACT

Thermoplastic compounds are used in several industrial, domestic and consumer applications. Thanks to their strength, lightness, flexibility and processing properties, they are also widely used for engineering purposes (EngTh). However, thermoplastics are often derived from polymers formed from non-renewable sources, such as oil. In addition, the production processes have a high consumption of energy. This research aims to evaluate the environmental impacts with the Life Cycle Assessment methodology of three polymers based on polyamide 6.6 modified with flame retardants (brominated polystyrene and antimony trioxide, aluminium diethylphosphinate and melamine polyphosphate, red phosphorus) and the influence of the replacement of the oil-based polyamide 6.6 with mechanical recycled polyamide on the sustainability of the production. The analysis was conducted using SimaPro v9.5 software, Ecoinvent 3.9.1 database and ReCiPe 2016 v1.07 impact assessment method. The primary data was collected in 2023 in a facility located in Italy. The results show that the impact of raw materials accounts for more than 95 % of the environmental profile in all three products considered, while the processes for the production and the subsequent transports are no more than 5 %. The analysis highlighted that up to 6–9 % of environmental benefits can be achieved by replacing only 10 % of oil-based PA 6.6 with mechanical recycled PA (MRPA), with the best results for RPm given the highest percentage of PA 6.6 in the initial mixture. The results of this assessment will be useful to promote the production of EngTh more sustainably.

Abbreviations

BPS-at	Brominated polystyrene and antimony trioxide
DMPP	Aluminium diethylphosphinate and melamine polyphosphate
EngTh	Engineering thermoplastics
FSS	Fossil resource scarcity
FU	Functional Unit
GF	Glass fiber
GW	Global warming potential
HCT	Human carcinogenic toxicity
HDPE	High-density polyethylene
LCA	Life Cycle Assessment
MRPA	Mechanical recycled polyamide 6.6
PA	Polyamide
PCR	Product Category Rules
PE	Polyethylene
PET	Polyethylene terephthalate
PLA	Polylactic acid
PM	Fine particulate matter formation
PP	Polypropylene
PS	Polystyrene
Pt	Point
PVC	Polyvinyl chloride
RPm	Red phosphorus

1. Introduction

Global plastic production reached approximately 400.3 million tons in 2022, and almost 90 % of this production is referred to thermoplastics (Nayanathara Thathsarani Pilapitiya and Ratnayake, 2024). Given that

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part of the plastics is generally recycled (more than 40 % in Europe (Eurostat, 2021)), some aspects of plastic waste management still represent a matter of concern (Amadei et al., 2023; Hu et al., 2019). This is also confirmed in the Circular Economy Measures discussed by the EU, according to which all plastic packaging will have to be recyclable and by 2029, 90 % of single-use plastic and metal beverage containers will have to be collected separately (EP, 2024). The barriers relate to the lack of reusable or recycled plastic markets and their quality and way of collection that is different from a country to another (Kumar et al., 2024; Rada, 2023; Rada et al., 2021; Satti et al., 2024). Due to the high stability, durability and recalcitrant nature of biodegradation, plastic waste tend to remain in the environment causing severe ecological, economic and social problems (Hurley et al., 2020; Wan et al., 2019; Wang et al., 2020; Williams and Rangel-Buitrago, 2019). Moreover, plastic waste not managed correctly can be the source of secondary pollution by microplastics, small particles with a size less than 5 mm that can cause health disruptions not only in wildlife but potentially also in humans (Carnevale Miino et al., 2024; Dehghani and Yunesian, 2024; Firouzsalari et al., 2024). Despite the limited and preliminary data, exposure to microplastics in humans seems to be related to accumulation in the liver, kidney, and brain (Hore et al., 2024; Vethaak and Legler, 2021).

Thermoplastics are widely used among plastic materials thanks to their excellent mouldability and low density (Sakaue, 2023). Thermoplastics' environmental impact is evident in every stage of plastic life, from the extraction of raw materials to the transportation, manufacturing and waste treatment (Shen et al., 2020). Due to their excellent formability and low-density properties, thermoplastics are extensively utilized in a wide range of products (Hosseini, 2024; Mă;rieş and Abrudan, 2018). Usually used in the design and manufacture of industrial products, the most common thermoplastics include polyamides (PA), polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polyethylene terephthalate (PET) (Biron, 2012).

PA, also known as nylon, is an engineering thermoplastic well known for its important properties and is currently used in automotive, construction and building sectors, textile fabrications, as well as in the electronic engineering sector (Hirschberg and Rodrigue, 2023; Li et al., 2016; You et al., 2024). Among the different PAs, PA 6.6 and PA 6 represent the two significant types currently produced, obtained by the condensation polymerization of, respectively, caprolactam and hexamethylene diamine with adipic acid (Douka et al., 2018). In order to implement commonly accepted safety measures, flame retardants are generally added to plastic (Babrauskas et al., 2014).

Regarding environmental impact, PA production generally includes oil-based raw materials, which implies important and several negative environmental impacts, such as fossil resource depletion with challenges in the recycling and restoration processes (Bhushan et al., 2023; Choi et al., 2023). Flame retardants can be seen as a potential source of concern in human health, given the interaction between potentially harmful chemicals and the human body (de Boer et al., 2024). For this reason, considering that the worldwide consumption of flame retardants is destined to grow around 3 % per year (2.4 million metric tons in 2019), the need to find alternative and environmentally friendly systems for their disposal gains importance (Miranda et al., 2022).

To better estimate the environmental sustainability of a product or process, the use of a Life Cycle Assessment (LCA) approach can be useful because it considers the entire environmental impacts, from the raw materials to the end of production (cradle-to-gate approach) or the end of life (cradle-to-grave) (Baltrocchi et al., 2024; Khan et al., 2023; Paoli et al., 2022; Rugani et al., 2019). LCA is a standardized methodology that follows the standards ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b). This comprehensive approach spans from the extraction of raw materials through production, distribution, use, and eventual disposal (Ferronato et al., 2023). LCA is an essential tool for assessing sustainability and facilitating informed decision-making, as it identifies environmental impacts and areas for potential improvement (Pell et al., 2021; van der Giesen et al., 2020; Ahmad et al., 2024). LCA analysis can be used in synergy with Life Cycle Costing (LCC) and Social Life Cycle Assessment (S-LCA) in order to improve environmental, economic and social sustainability (Baltrocchi et al., 2023; Aqib et al., 2024).

In literature, several studies tried to evaluate the environmental performance of engineering thermoplastics (EngTh) from the mechanical to the electronic and electrotechnical area (Gagliardi et al., 2021; Galve et al., 2022; Hernández-Díaz et al., 2021; Melo de Lima et al., 2023). For instance, Delogu et al. (2015) evaluated the environmental performance of automotive parts composed of two alternative materials (PP vs PA), highlighting that substituting PA with PP reduces the potential environmental impacts for all the categories. Korol et al. (2016) compared the environmental impacts of plastic pallets based on PP, glass fiber (GF) and natural fibres, pointing out that it is impossible to assess unequivocally which material has the lowest impact on the environment. Vidal et al. (2018) focused on the environmental sustainability of aircraft interior panels composed of PP and polylactic acid (PLA) showing that better environmental performances than conventional panels can be achieved. Nguyen et al. (2020) evaluated the global warming potential (GWP) of different high-density polyethylene (HDPE) based piping system alternatives and found that bio-based polymers HDPE help to reduce costs and environmental impacts for long-lived pipe assets. Additionally, La Rosa et al. (2021) used LCA to estimate the environmental impacts of conductive polymer composites made of HDPE recovered from municipal solid wastes used as electromagnetic interference shielding material. Further studies compared oil-based PA 6.6 with other types of plastics (He et al., 2022; Seile et al., 2022; Tinz et al., 2023). For instance, Mio et al. (2021) found that PA 6.6 with 30 % wt. GFs mixed with phosphate-based flame retardants was the optimal solution for the replacement of aluminium traditional covers in the maritime industry. In another study, Maga et al. (2024) assessed the environmental impacts of aluminium diethylphosphinate and brominated polystyrene flame retardants in PAs for use in the electronic field, highlighting that the flame-retardant polyamides using aluminium diethylphosphinate has a higher environmental sustainability than the ones using halogenated flame retardants.

The studies in literature have highlighted the impacts of EngTh PA-based, however, to date, there is still no data regarding the environmental benefits that could derive from the use of recycled polymer. This work therefore represents the first attempt to quantify the improvement in environmental sustainability that can be achieved by replacing oil-based PA with mechanical recycled PA (MRPA).

This study aims to (i) assess the environmental impacts of three EngTh based on PA 6.6 reinforced with GF and three distinct flame retardants (brominated polystyrene in combination with antimony trioxide, aluminium diethylphosphinate in combination with melamine polyphosphate, and red phosphorus), considering the impacts from the extraction of raw materials up to the distribution platform and (ii) evaluate the effect of oil-based PA replacement with MRPA. This study does not present methodological innovation, as the standard LCA methodology has been applied to a case study. However, this assessment can be considered an example of eco-design that is convenient to increase consciousness about the importance of stimulating the use of recyclable materials. These results will be useful both for the scientific community and technical stakeholders involved in the production and management of EngTh.

2. Methods

2.1. Goal and scope definition

The analysis aims to evaluate and compare the environmental performance of three EngTh with the scope to understand the environmental benefits derived from the introduction of MRPA in different rates. The products are named according to their flame retardants: (i) brominated polystyrene and antimony trioxide (BPS-at), (ii) aluminium diethylphosphinate and melamine polyphosphate (DMPP) and (iii) Red phosphorus (RPm). The assessment considered the production of raw materials and the factory compounding processes. Furthermore, the supply of energy, the use of packaging, emissions into the atmosphere and the final disposal of waste were taken into account.

The research wants to answer two main questions.

(i) What are the environmental performances of the three products?
(ii) What are the benefits derived from the introduction of the replacement of the oil-based PA with MRPA as mitigative solution?

The LCA analysis was carried out using SimaPro v9.5 software (PRé Sustainability BV, 2023) and ReCiPe 2016 v1.07 Hierarchist impact assessment method at mid-point and end-point levels (Goedkoop et al., 2009). The normalized environmental impacts are reported in mPt, where Point (Pt) is a measurement unit representative of one-thousandth of the yearly environmental load of the average European inhabitant (Paoli et al., 2022). The normalized results allow for comparing different impact categories, helping to identify the most significant impacts and identify critical points. The scheme of the research followed the Product Category Rules (PCR) 2010:16 Plastics in primary forms v3.0.2 (EPD International AB, 2022) from the extraction of raw materials up to the distribution to the distribution platform. Considering these EngTh are generally used in engineering after an injection process, 1 L of the final product was considered as the Functional Unit (FU). While the primary technical function (flame retardancy) is often maintained by increasing the MRPA content (LATI, 2016; LATI, 2022), the different technical properties of MRPA may potentially lead to a different design of the injection moulded part to maintain the mechanical properties, eventually modifying the quantity of material used downstream the system boundaries of this study.

2.1.1. System boundaries

As reported in the PCR, the life cycle of these EngTh was divided into three phases: upstream, core, and downstream (Fig. 1):

Upstream processes. This phase encompasses the production of raw materials, the manufacturing of packaging for both raw materials and the final product, and the transportation of materials to the factory. Additionally, it includes all the impacts associated with using electricity and fuels to produce products and transportation.

Core processes. This phase includes all the production processes conducted within the company, such as manufacturing and auxiliary production services. It also involves the treatment of waste generated within the facility and using electricity, water, and methane within the factory.

Downstream processes. The final phase involves the average product transportation from the facility to a customer, including packaging.

2.1.2. Products characterization

The three products are self-extinguishing EngTh polyamide-based with different flame retardants. The self-extinguishing EngTh assessed limit the risk of fire in electrical and electronic, home appliance and e-mobility applications and are optimized for UL94 flame retardancy tests, for GWIT, GWFI and GWEIPT glow wire tests under the IEC60335 standards, and for UL746b temperature ageing tests (LATI, 2024) (Fig. S1).

The three compounds had similar composition, mainly PA 6.6 and GF, but differed for the flame retardant (Table 1): (i) brominated polystyrene combined with antimony trioxide in BPS-at (final compound density 1.55 g cm^{-3}), (ii) a mixture of aluminium diethylphosphinate and melamine polyphosphate in DMPP (final compound density 1.40 g

Table 1
Composition of the three different EngTh in the current scenario (S0). Percentages are expressed on a mass basis. EngTh: engineering thermoplastics; PA 6.6: polyamide 6.6; GF: glass fiber; BPS-at: Brominated polystyrene and antimony trioxide; DMPP: Aluminium diethylphosphinate and melamine polyphosphate; RPm: Red phosphorus.

EngTh	PA 6.6 [%]	GF [%]	Flame retardant			Other [%]
			BPS-at [%]	DMPP [%]	RPm [%]	
S0_BPS-at	43–46	25–28	21–24	–	–	<15
S0_DMPP	43–46	25–28	–	21–24	–	<15
S0_RPm	49–52	25–28	–	–	10–12	<15

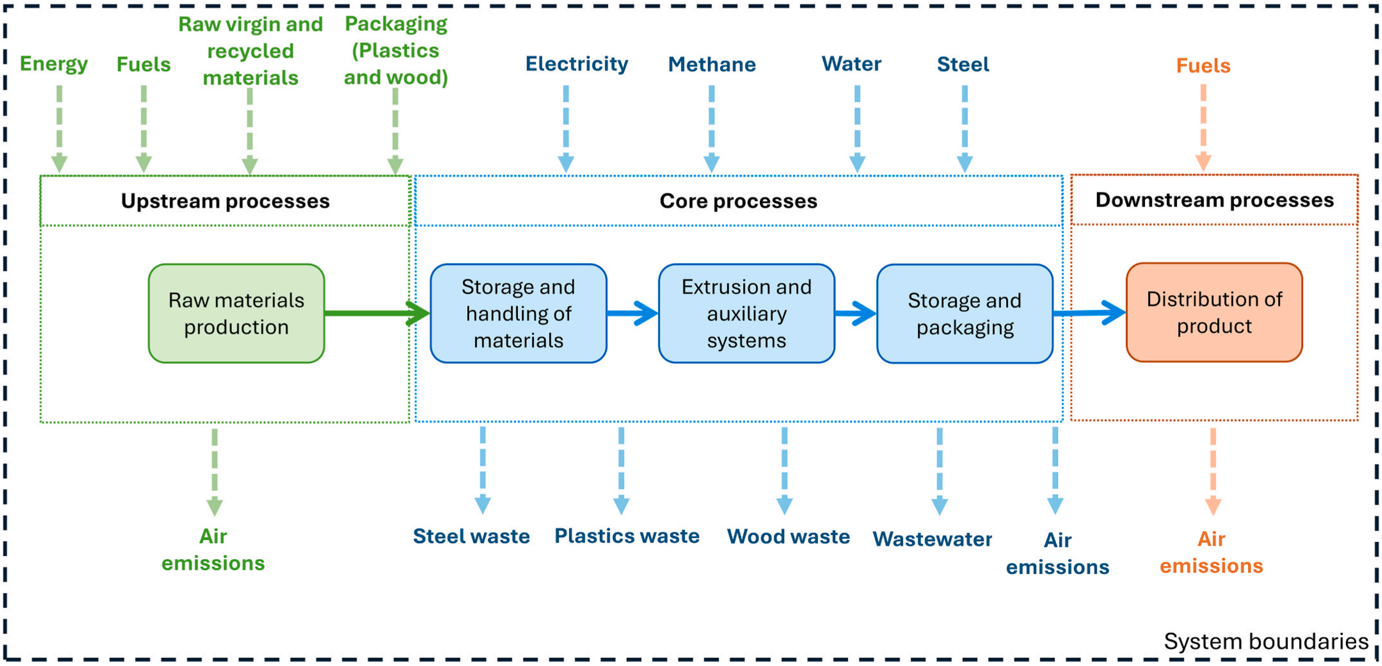

Fig. 1. System boundaries for the LCA.

cm^{-3}), and (iii) red phosphorus in RPm (final compound density 1.34 g cm^{-3}). For the development of the LCA analysis, if a range has been collected in LCI, the average value was considered.

2.1.3. Mechanically recycled polyamide 6.6 scenarios

In order to assess the impact of the substitution of the oil-based PA 6.6 with MRPA, different scenarios with diverse replacement rates were assumed (Table 2). S1, S2, S3, S4, S5, and S6 refer to a replacement rate equals to 10 %, 30 %, 50 %, 70 %, 90 %, and 100 %, respectively. These values were chosen to be representative of the current product range of manufacturer but also to steer eco-design towards the development of new grades, including higher recycled content as compared to the current product range of the manufacturer, considering potential future improvement of the MRPA quality. The use of MRPA is reflected only in the upstream phase, and no differences compared to the use of oil-based PA6.6 involved the core and the downstream phases.

2.2. Life cycle inventory (LCI)

The primary data was collected in 2023 in a facility near Varese (Italy) that produces thermoplastic compounds for engineering uses. Background processes for the upstream phase have been sourced from all materials associated with the products using the Ecoinvent v3.9.1 database (Frischknecht et al., 2005). As geographical boundaries, in the use of the database, the data referred to Italy (IT) was chosen and, if not available, to Europe (ReR). If these ones were not available, the impact data of the rest of the world (RoW) or the global one (GLO) were chosen.

The upstream stage includes all the impacts associated with using electricity and fuels to produce raw materials and transportation. According to the information provided by the facility, the flame retardants and GF were packed in big bags (1 ton) on wooden pallets (25 kg) and transported by trucks and ships, while PA 6.6 was moved using tank trucks. Table S1 lists all inputs and outputs associated with the production of upstream processes, and Table S2 details the transportation of raw materials and other materials.

The core stage includes the electricity, natural gas (i.e. methane) and water consumption inside the factory, the maintenance materials, and the treatment of waste generated and subsequently disposed. The production process of EngTh is characterized by complex processing (Fig. S2), the core of which is the multi-stage intimate incorporation, with a temperature profile of up to 300 °C, into the predominant polymer matrix brought to a molten state. A package of additives and reinforcements with different functions, such as pigments, self-extinguishing agents, antioxidants, lubricants and GFs, are amalgamated into this PA matrix. The central step in the process, which follows the dry blending phase in the batch and precedes pelletizing, is hot extrusion using proprietary technology using co-rotating twin-screw motors on different segments with high torque motors. This step is crucial to ensure the indispensable homogeneity of the compound under the specified pressure and temperature conditions. The key element that gives the product its main characteristic is the flame retardant, BPS-at, DMPP or RPm, which provides high-level self-extinguishing properties (UL Product IQ, 2024). In addition, the effective combination of organic antioxidants and type E GFs, appropriately sized and introduced at an advanced stage of the extrusion process, gives the material the long-lasting mechanical properties required for industrial applications. Table S3 reports all input and output associated with core processes.

The final phase (downstream) involves transporting the final product (including packaging) from the facility to a distribution platform. The transportation uses trucks (EURO 6) with capacities ranging from 7.5 to 16 metric tons (details are available in Table S4).

In case of scenarios with the replacement of virgin PA 6.6, MRPA was modelled by modifying the process Ecoinvent database v3.9.1 called “Polyethylene, high density, granulate, recycled {Europe without Switzerland}| polyethylene production, high density, granulate, recycled | Cut-off, U". In detail, the input process “Waste polyethylene, for recycling, sorted {Europe without Switzerland}| market for waste polyethylene, for recycling, sorted | Cut-off, U″ has been replaced with “Plastic flake, consumer electronics, for recycling {GLO}| market for plastic flake, consumer electronics, for recycling | Cut-off, U". This process represents the collection, treatment and recycling of thermoplastic products used in electronics.

Table 2
Composition of the three different EngTh in the diverse scenarios evaluated for oil-based PA 6.6 replacement with MRPA. Percentages are expressed on a mass basis. EngTh: engineering thermoplastics; PA 6.6: polyamide 6.6; MRPA: Mechanical recycled polyamide 6.6; GF: glass fiber; BPS-at: Brominated polystyrene and antimony trioxide; DMPP: Aluminium diethylphosphinate and melamine polyphosphate; RPm: Red phosphorus.

EngTh	PA 6.6 [%]	MRPA [%]	GF [%]	Flame retardant			Other [%]
				BPS-at [%]	DMPP [%]	RPm [%]	
BPS_at							
S1_BPS-at	38–40	3–5	25–28	22–24	–	–	<15
S2_BPS-at	29–31	11–13	25–28	22–24	–	–	<15
S3_BPS-at	20–22	20–22	25–28	22–24	–	–	<15
S4_BPS-at	11–13	29–31	25–28	22–24	–	–	<15
S5_BPS-at	3–5	37–39	25–28	22–24	–	–	<15
S6_BPS-at	–	42–44	25–28	22–24	–	–	<15
DMPP							
S1_DMPP	39–41	3–5	25–28	–	21–24	–	<15
S2_DMPP	30–32	12–14	25–28	–	21–24	–	<15
S3_DMPP	21–23	21–23	25–28	–	21–24	–	<15
S4_DMPP	12–14	30–32	25–28	–	21–24	–	<15
S5_DMPP	3–5	39–41	25–28	–	21–24	–	<15
S6_DMPP	–	44–46	25–28	–	21–24	–	<15
RPm							
S1_RPm	44–46	4–6	25–28	–	–	10–12	<15
S2_RPm	34–36	14–16	25–28	–	–	10–12	<15
S3_RPm	24–26	24–26	25–28	–	–	10–12	<15
S4_RPm	14–16	34–36	25–28	–	–	10–12	<15
S5_RPm	4–6	44–46	25–28	–	–	10–12	<15
S6_RPm	–	50–52	25–28	–	–	10–12	<15

3. Results

3.1. Current scenario: what is the most environmentally friendly EngTh?

The outcomes of the environmental profile per 1 L of EngTh produced are reported in Fig. 2a. The results indicate that S0_BPS-at determine the highest impact (362 mP t per L), followed by S0_DMPP (345 mP t per L) and S0_RPm (315 mPt). The use of DMPP and RPm as flame retardants allow to reduce the environmental impact of almost 5 % and 13 %, respectively, compared to the case in which BPS-at is used. The upstream phase contributes significantly more than the other phases, counting 94 % of the total environmental impact in S0_BPS-at, 94 % in S0_ DMPP and 95 % in S0_RPm. A closer examination of the upstream contribution reveals that the PA 6.6 production is responsible for the highest impact across all EngTh: almost 58 %, 55 %, and 61 % of the total impact in S0_BPS-at, S0_DMPP and S0_RPm, respectively. On the contrary, the impact of the flame retardant is limited: almost 17 %, 11 % and 16 % of the total in S0_BPS-at, S0_ DMPP and S0_RPm, respectively. The other phases have a significantly lower impact than the upstream; the core contributes to the total impact with 4.9 % in S0_BPS-at, 5.5 % S0_ DMPP and 4.7 % S0_RPm, while the downstream reports values lower than 1 % in all the EngTh.

Regarding endpoint categories (Fig. 2b), the most affected category is human health for all three products. In detail, the values are 343 mP t per L in S0_BPS-at (95 % of the total), 326 mP t per L in S0_ DMPP (94 %) and 296 mP t per L in S0_RPm (94 %). The results highlight that the other endpoint categories (ecosystems and resources) account for less than 5 % of the total. The primary source of the impacts in the human health category is the emissions caused by electricity consumption in PA 6-6 production (upstream phase).

3.2. How to reduce the impact? The use of recycled polyamide 6.6

Generally, MRPA in upstream phases decreases impacts in all categories. The environmental profile shown in Fig. 3 reports a range of benefits for various scenarios when compared to the baseline S0 scenario. The S1 scenarios (Fig. 3a), including S1_BPS-at, S1_DMPP, and S1_RPm, show modest environmental benefits, with improvements of 9.4 % (328 mPt), 9.7 % (311 mPt), and 5.9 % (283 mPt), respectively. In the S2 scenarios (Fig. 3b), the reductions are −17.9 % (297 mPt) for S2_BPS-at, −17.8 % (283 mPt) for S2_ DMPP, and −19.8 % (252 mPt) for S2_RPm. This trend of positive impact continues in the S3 scenarios (Fig. 3c), with reductions of −26.4 % (266 mPt) for S3_BPS-at, −26.0 % (255 mPt) for S3_ DMPP, and −29.7 % (221 mPt) for S3_RPm. The S4 scenarios (Fig. 3d) show even more significant positive impacts, with −34.9 % for S4_BPS-at (236 mPt), −34.2 % for S4_ DMPP (227 mPt), and −39.4 % for S4_RPm (191 mPt). The benefit intensifies in the S5 scenarios (Fig. 3e), with reductions of −43.4 % for S5_BPS-at (205 mPt), −42.3 % for S5_ DMPP (199 mPt), and −49.3 % for S5_RPm (160 mPt). Finally, the S6 scenarios record the most positive impacts (Fig. 3f), with reductions of −47.6 % for S6_BPS-at (190 mPt), −46.4 % for S6_ DMPP (185 mPt), and −54.2 % for S6_RPm (144 mPt).

The environmental impacts as a function of PA6.6 replacement; the impacts tend to decrease, increasing the oil-based PA 6.6 replacement ratio (Fig. 4a). BPS-at and RPm show the hugest drop with a reduction of 178.3 mP t PA 6.6 MRPA^{-1} and 175.4 mP t PA 6.6 MRPA^{-1}, respectively. Focusing on human health (Fig. 4b), the total replacement of oil-based PA 6.6 with MRPA determines the reduction of almost 46.9 %, 45.7 %, and 53.7 % of the impacts in case of the use BPS-at, DMPP and RPm, respectively. A PA 6.6 replacement rate of 15 % and 10 % in case of BPS-at and DMPP, respectively, is enough to reach the same environmental impact given by RPm without using MRPA. Regarding the ecosystems impact category (Fig. 4c), the most significant reductions are observed in BPS-at with 6.74 mP t, followed by RPm with 6.67 mP t and DMPP with 6.28 mP t. Finally, in terms of resources (Fig. 4d), the situation is similar to the previous impact category, with BPS-at reporting the hugest drop (5.16 mP t) followed by RPm and DMPP with 5.12 mP t and 4.79 mP t, respectively.

4. Discussion

The huge increase in global plastic production and consumption made it necessary to rethink the approach in which these compounds are produced. Nowadays, EngTh are widely used in several industrial sectors due to their excellent properties. This work aims to present a proof of concept of the environmental sustainability of three different real EngTh which mainly differs for the flame retardants added in the mixture. Moreover, based on the authors knowledge, for the first time, the effect of oil-based PA 6.6 replacement with MRPA for the production of EngTh has been evaluated.

The results show that the environmental profile is similar across the three EngTh due to the low impact of different flame retardants used (ranging from 11 to 17 % of the total). On the contrary, the upstream phase accounts for most of the impacts (around 94 % of the total). This is mainly due to the production of raw materials, particularly PA 6.6. The huge profile of environmental impact of PA 6.6 has also been confirmed in previous studies (Delogu et al., 2015). The core phase of production of the EngTh is the less source of environmental impacts (less than 5 % of the total), while the downstream is substantially negligible for all the EngTh considered in the analysis. In terms of green industrial applications, these results suggest that to further minimize the impact of EngTh, the efforts should not be focused on the production step but on using more sustainable raw polymers (in this case, PA 6.6).

The analysis highlighted that up to 6–9 % of environmental benefits

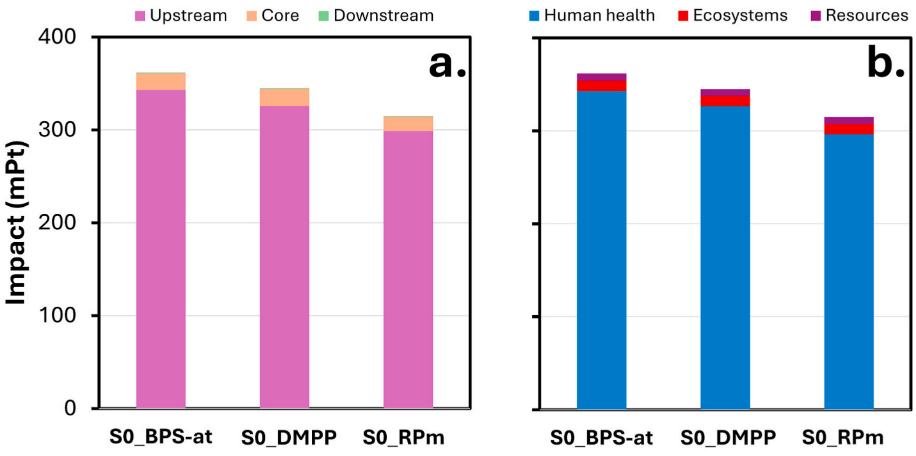

Fig. 2. Environmental impacts of scenario S0 per (**a**) process phases and (**b**) per endpoint categories. FU: 1 L of EngTh produced.

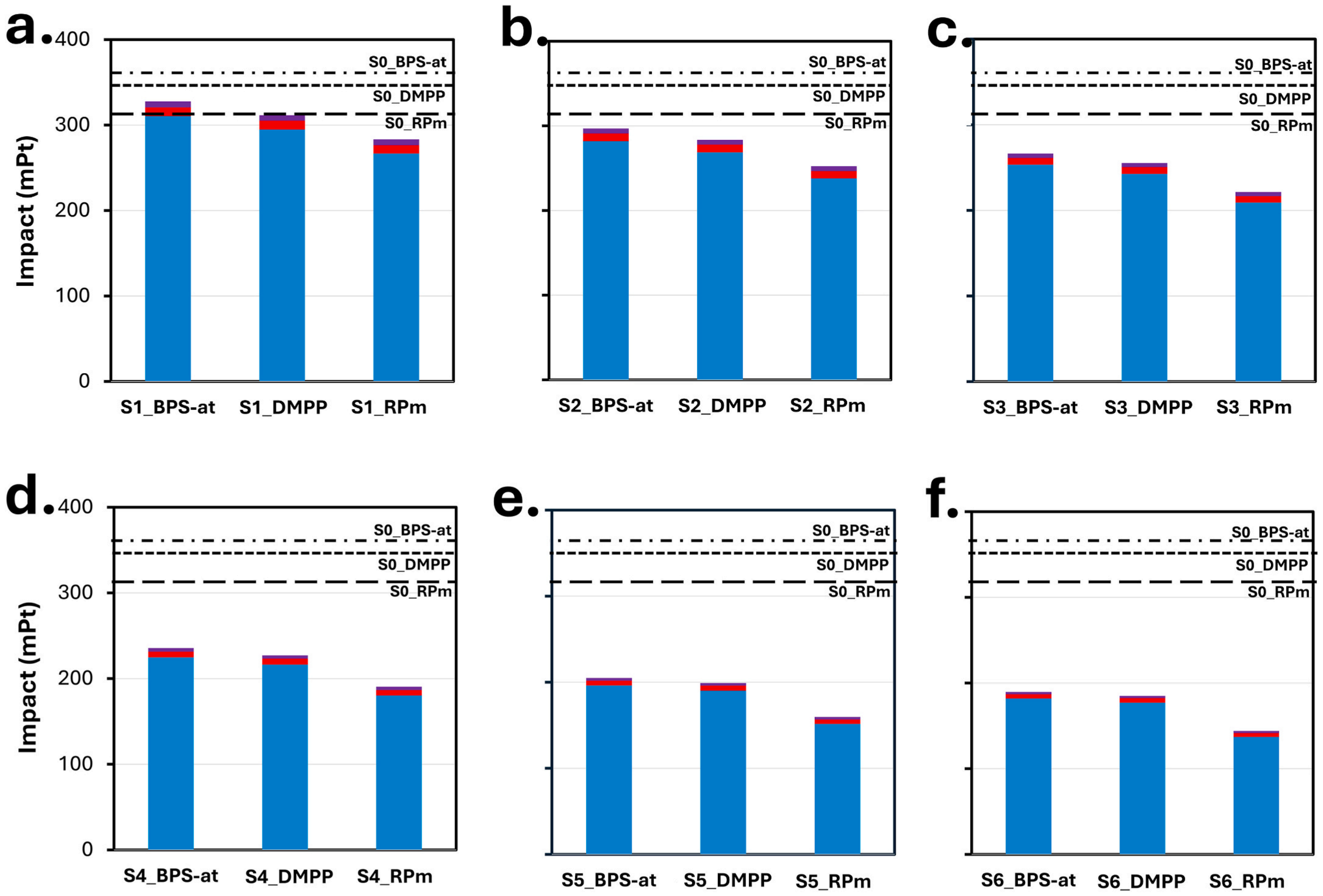

Fig. 3. Comparisons of MRPA scenarios: (**a**) S1, (**b**) S2, (**c**) S3, (**d**) S4, (**e**) S5 and (**f**) S6. Light blue and red indicate effects on human health and ecosystems. Violet refers to resources depletion. FU: 1 L of EngTh produced. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

can be achieved by replacing with MRPA only 10 % of oil-based PA 6.6 contained in EngTh in S0. This result can be mainly attributed to a consistent decrease in almost all impact categories, such as global warming potential (GW), fine particulate matter formation (PM), freshwater eutrophication, human carcinogenic toxicity, and fossil resource scarcity (FSS) (Table S5). For instance, with BPS-at, GW decreases from 9.80 to 9.24 $kg_{CO2,eq}$ per L of EngTh, and HCT drops from 12.4 to 7.7 $g_{PM2.5,eq}$ per L of EngTh in S0 and S1, respectively. Given that RPm has the highest percentage of PA 6.6, it reports the most benefits from introducing recycled raw material (up to 46 % in case of a complete oil-based PA 6.6 replacement). For instance, GW decreases from 9.48 to 3.87 $kg_{CO2,eq}$ per L of EngTh HCT drops from 9.54 to 4.78 $g_{PM2.5,eq}$ per L of EngTh in S0 and S6, respectively. The environmental benefits in case of BPS-at and DMPP are very encouraging. Up to 35–39 % of reduction of environmental impacts when MRPA is used as substitution material of the 70 % of oil-based PA 6.6. For instance, GW decreases from 9.80 to 5.90 $kg_{CO2,eq}$ per L of EngTh in case of BPS-at and from 9.55 to 5.99 $kg_{CO2,eq}$ per L of EngTh in case of DMPP. FSS decreases from 3.11 to 1.84 $kg_{oil,eq}$ per L of EngTh in case of BPS-at and from 2.95 to 1.79 $kg_{oil,eq}$ per L of EngTh in case of DMPP. Nowadays, comparing these results with the previous literature is not easy since this study represents the first attempt to evaluate the environmental benefits of replacing virgin polymer with MRPA.

In terms of an industrial application, the main aspect that is still unclear is the optimal point for the replacement of oil-based PA 6.6 with MRPA to increase the environmental sustainability of the products while at the same time maintaining the same properties of the final thermoplastics (considering that a full replacement is a not realistic case). This aspect should be further investigated in the future.

This work demonstrates that using alternative recycled materials to produce EngTh significantly increases the environmental sustainability of the products by reducing their overall impact. For a green turning point in the plastic production sector for engineering use, attention should be focused on the study and development of products capable of maintaining or increasing performance while reducing the consumption of oil-based polymers. The impact of the different flame retardants is more limited, at least in the context studied, but still to be considered to further reduce the impact of EngTh production.

One of the main limitations of the present study is the assumptions made during the definition of the model and the impact method used for carrying out the LCA analysis. In this sense, a further step of the research could be to acquire a primary data model of mechanical recycling, which could better describe the specific case studies instead of proxy data. In the future, the analysis can also be expanded by evaluating the possible reuse of other recycled materials (e.g., chemicals) and taking into consideration the end-of-life of the products. In this case, using prospective LCA, integrated with patent analysis, to estimate the environmental sustainability of different scenarios of immature new products as a decision-making tool for industrial purposes gains importance (Spreafico et al., 2023).

An economic evaluation can also be useful to estimate the optimal replacement point for oil-based PA 6.6 ensuring that the production of EngTh remains economically sustainable for the market. Moreover, this work does not currently assess the potential impacts of the use of MRPA

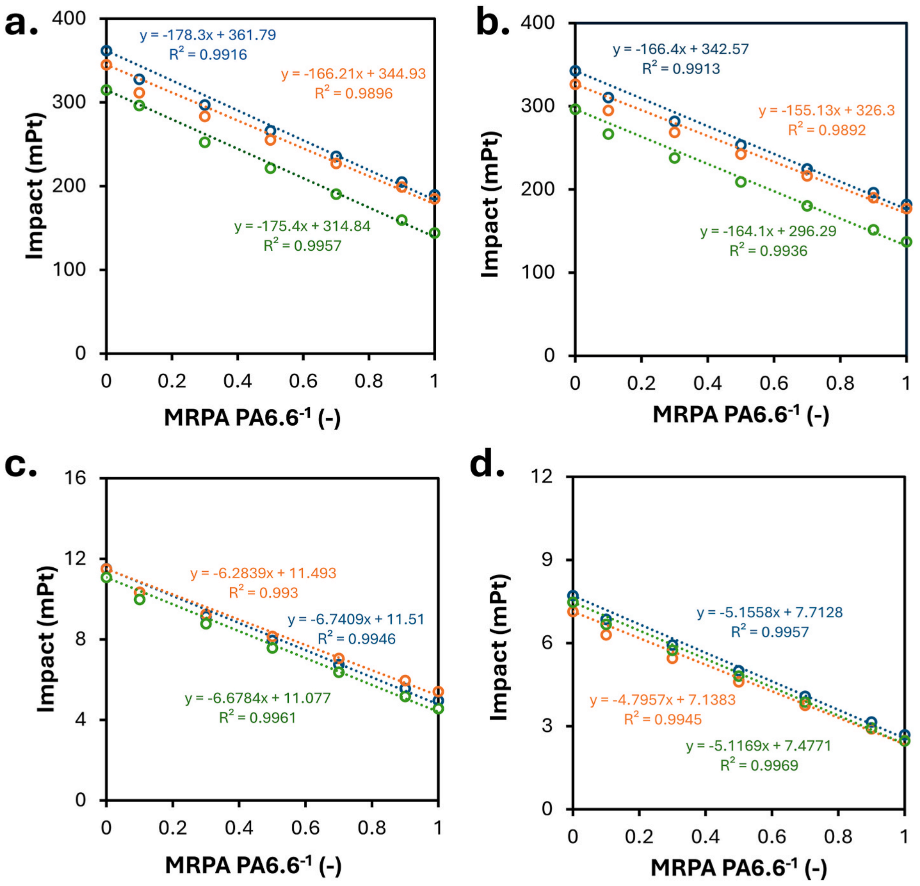

Fig. 4. (**A**) Total, (**b**) human health, (**c**) ecosystems, and (**d**) resources impacts as a function of oil-based PA 6.6 replacement with MRPA. Blue, orange and green indicate the cases in which BPS-at, DMPP and RPm were used as flame retardants, respectively. FU: 1 L of EngTh produced. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

on the design of the injection moulded part. This is outside the scope of this study, and further assessments will be needed to shed light on the potential modification of the material used in the downstream phase due to the different mechanical properties of MRPAs.

5. Conclusions

This study evaluated the environmental profile of three PA-based compounds with different flame retardants (BPS-at, DMPP and RPm) and the benefits of replacing the oil-based PA 6.6 with MRPA. The environmental analysis showed that the upstream phase significantly contributes to the impacts for all compounds, with an average share of 95 % of the total, mainly in the human health endpoint category (around 94 % of the total). Regarding the MRPA scenarios, the analysis highlighted the benefits that led to the introduction of recycling PA 6.6. The findings showed that introducing recycled polymers decreased the environmental impacts up to 35–39 % in case of 70 % replacement. This study contributes to the scientific literature by proposing a new perspective on mitigating environmental impacts in EngTh production. This research shows the need to introduce recycled material and study new possibilities that allow a total replacement of oil-based polymers to enhance the sustainability of thermoplastic compounds for engineering use. Further studies are needed to overcome some limitations of the present work, such as the use of primary data also for mechanical recycling and the necessity to shed light on the potential modification of material used in the downstream phase due to different mechanical properties of MRPAs that may lead to a different quantity of material been used for the manufacturing of the injection moulded part.

CRediT authorship contribution statement

Alberto Pietro Damiano Baltrocchi: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Davide Lotti:** Writing – review & editing, Validation, Resources, Conceptualization. **Marco Carnevale Miino:** Writing – review & editing, Visualization, Validation, Methodology. **Lucrezia Maggi:** Writing – original draft, Investigation. **Elena Cristina Rada:** Writing – review & editing, Validation. **Vincenzo Torretta:** Validation, Supervision, Project administration.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Davide Lotti has been working for the company LATI Industria Termoplastici S. p.A. The remaining authors declare that the research was carried out in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2025.145769.

Data availability

All data generated or analyzed during this study are included in this published article.

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