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High performance thermoplastic (HPTP) producers are looking at effective ways to mitigate the environmental impacts of HPTP products to remain competitive on the long term given the increasing demand of HPTPs. However, effective mitigation measures cannot be designed without deep investigation into HPTP supply chain. Using LCA, we show that feedstock sourcing and processing energy are the main drivers of environmental impacts of HPTPs. Direct $CO_2$ emissions from production of HPTPs are very low, meaning mitigation strategies based on carbon capture and storage would have minor effects on environmental impacts of HPTPs. It identifies recycling and sustainable feedstock as effective mitigation strategies in HPTP industries. Our work contributes to the UN's Sustainable Development Goals *climate action and sustainable production consumption*

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# Environmental impacts of three high-performance thermoplastics (HPTPs) and associated glass-fiber reinforced grades under different processing technologies

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## Abstract

To inform the design of effective mitigation strategies for high performance thermoplastics (HPTPs) we assessed the environmental impacts of three varieties: polyetherimide (PEI) and polyphenylene sulphide (PPS), polybutylene terephthalate (PBT) and related glass-fiber reinforced grades. Using data collected from different sources and the life cycle assessment (LCA) method, we showed that direct $CO_2$ emissions from HPTP production were low and that the environmental performance of HPTPs was primarily driven by feedstock sourcing and processing method. Feedstocks were responsible for 35% -93% of non-renewable energy (NRE) usage followed by the process energy (4% - 49%), and glass fiber (0 -12%). HPTP manufacturing processes using thermoforming consumed the most NRE, and those using extrusion consumed the least. Total NRE consumption ranged from 248 – 370 MJ $kg^{-1}$ for PEI, 103 –183 MJ $kg^{-1}$ for PPS, and 101 –115 MJ $kg^{-1}$ for PBT. Glass-fiber reinforced grades reduced NRE use by 13% - 36% relative to unfilled HPTPs. GHG emissions showed a similar trend and ranged from 12-17 kg $CO_{2eq}$ $kg^{-1}$ for PEI; 7 – 9 kg$CO_{2eq}$ $kg^{-1}$ for PPS, and 4 – 5 kg $CO_{2eq}$ $kg^{-1}$ for PBT. Eutrophication (EP) and acidification (AP) were low and followed the PEI > PPS >PBT trend. Low direct $CO_2$ emissions from HPTP manufacturing limit the potential for point source carbon capture and storage as a mitigation strategy. However, developing recyclable, green feedstocks and adopting eco-friendly process are key for improving the sustainability of HPTPs. Our findings serve as important reference for HPTPs stakeholders and policy makers.

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# Introduction

High performance thermoplastics (HPTPs) are polymers that exhibit exceptional thermomechanical properties and can withstand high temperatures (≥ 150°C) without decomposition or loss of thermomechanical properties and chemical stability[1]. HPTPs offer several advantages over thermosets, including rapid processing and enhanced formability through techniques like additive manufacturing and injection moulding [2]. Compared with metals, they possess higher stiffness-to-weight and strength-to-weight ratios, greater fatigue and corrosion resistance, and higher design freedom[3]. Because of these attributes, HPTPs are highly desired in the aeronautic, electronic, automotive, 3D printing, and building industries where they displace other materials like metals[4].HPTPs can be grouped into amorphous such as polyetherimide (PEI) and semi-crystalline polymers like polyphenylene sulfide (PPS) and Polybutylene terephthalate (PBT) [5]. HPTPs are often filled with glass fiber or other materials like carbon fiber and minerals to enhance their mechanical properties and provide new properties. Although HPTPs and associated glass fiber grades are inexpensive, each is a highly engineered material with precise physical and mechanical properties. They can be molded into any desired shape through rotation, injection, extrusion, compression, blowing or thermoforming and their material properties are adjusted during and/or after synthesis to achieve the desired strength, permeability, porosity, opacity and color.

The global production of HPTPs reached 0.8 million tons in 2022 [6], and this annual production volume will continue to grow due to strong demand in end-users' markets such as electronic, aeronautic and automotive, and the growing emphasis on sustainability. However, with the fossil fuels as the primary feedstocks, HPTPs are inextricably tied to carbon emissions and therefore climate change While HPTPs offer plethora of benefits and are fundamental in the production of several high-tech products, their sustainability can be a limiting factor for their further deployments [7]. In fact, the vast majority of HPTPs produced today, including PEI, PPS, and PBT are primarily derived from fossil fuels such as crude oil and natural gas. These resources are processed into monomers, which are chemically bounded to form HPTP resins. The manufacturing of HPTPs is energy-intensive, releases greenhouse gas (GHG), acidifying compounds ($SO_2$), and generates wastes which all have significant consequences for the environment and human health[8–10]. Moreover, the polymerization of HPTPs often requires high temperature and use of aromatic hydrocarbon which in turn also depend on the crude oil refining process [11]. Plastic (incl. HPTP) pollution has become one the most pressing environmental issues of this century. Each year, million ton of plastic wastes end up in landfills, oceans and natural habitats, causing significant damage to ecosystems and wildlife. Despite the increased attention given to plastic pollution in the last decade, evidence suggests thar the problem is worsening [12]. Recent public consultations on increasing plastic pollution identified the need to tackle the environmental impacts of plastics at the design and manufacturing phase and the importance of providing information related to potential environmental impacts of plastics as the two key messages among others [13]. Production of HPTPs is technically more challenging and their carbon footprints can also be significantly higher than those of commodity plastics [14]. The increasing market share of HPTPs calls for a broader understanding of their implications at the environmental level. Consequently, gaining insight into the manufacturing processes and associated environmental impacts (incl. non-renewable energy (NRE) consumption, carbon footprint, acidification, eutrophication) of various HPTPs can help HPTP industries make informed choices and contribute to a cleaner and healthier world [15]. Unfortunately, very little information exists in the literature regarding the environmental impacts of HPTPs [16,17].

Existing studies on environmental impacts of plastics are those related to commodity plastics such as low- and high-density polyethylene, polyvinyl chloride, polylactic acid, polystyrene, polycarbonate, polyethylene terephthalate, polyurethane polyphthalamide, polypropylene[18]. Most of these studies focused on the end-of-life options of these commodity plastics and they show that landfilling and mechanical/mechanical recycling are the end-of-life options with lowest carbon footprints[19–21]. A few of these studies explored the environmental impacts of commodity plastics production, and concluded that feedstock procurement and processing are the main contributor to environmental impacts of commodity plastics [22–25]. Among commodity plastics, bioplastics are reported to have low carbon footprint [26,27] and are typically less-energy and water intensive to produce than conventional plastics [28–30] . For example, Shen et al.[31] show that biobased polyethylene terephthalate consumed 20% less NRE than the conventional polyethylene terephthalate. The carbon footprint of bioplastics was also reported to be much lower when produced from renewable power sources than using fossil-fuel based grid mix power [32]. Studies on environmental impacts of HPTP production are very scarce[33], although it is well known that its production is responsible for substantial environmental [16] and health impacts[34]. One of the few available studies on HPTPs found that the production of polyoxazolidinone a novel HPTP has low GHG emissions relative to polyetherimide (PEI)[14]. Another study found that polyamide 6.6

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when reinforced with glass fiber had better environmental performance than the traditional aluminum covers in the marine industry[35]. Delogu et al[35] concluded that substituting polyamide composite with polypropylene composite reduced the potential environmental impact in all categories and each of the stage of the air intake manifold, while Korol et al.[30] argued that it is impossible to assess unequivocally which of these two composite materials has the lowest impacts on the environment. Overall, these latest researches highlighted some of the potential environmental impacts of HPTPs, but the analysis is limited, in many cases, to few impact categories, ignoring thus the major trade-offs that may exist when most impacts categories are considered. As results, effective mitigation strategies cannot be established without a comprehensive understanding of full impacts of HPTP production. This study *(i)* assesses the potential environmental impacts of three HPTPs (PEI, PPS, PBT) and their related glass-fiber reinforced grades (PEI30GF, PEI45GF, PPS40GF, PPS65GF, PBT40GF and PBT45GF), *(ii)* analyse the emission characteristics and provide emissions reduction strategies in line with the development characteristic of HPTP industries in Europe.

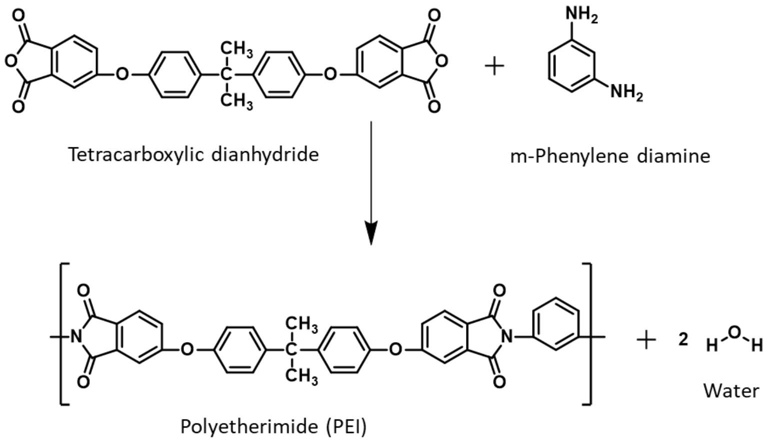
## Material and methods

### HPTPs studied and production pathways

Three HPTPs namely polyetherimide (PEI), polyphenylene sulfide (PPS), polybutylene terephthalate (PBT) and their associated glass-fiber filled grades (PEI30GF, PEI45GF; PPS40GF, PPS65GF, PBT40GF and PBT45GF), were considered in this study. The main difference between these HPTPs is that PEI an amorphous HPTP goes from soft to hard states more gradually, while both PPS and PBT, which are semi-crystalline HPTPs become hard at certain temperature. Further details on the production and processing pathways of the studied HPTPs and associated glass-fiber filled grades are given below.

### Polyetherimide (PEI)

PEI is an amorphous HPTP known to exhibit high temperature resistance, outstanding mechanical properties and excellent dielectric properties. It is produced by polycondensation reaction between aromatic dianhydrides and aromatic diamines. Its synthesis begins with the production of an intermediate poly (amic acid) from the reaction of a dianhydride and a diamine. This intermediate undergoes a chemical imidization process to form the final product PEI (Equation 1). PEI can be reinforced with glass fiber (PEI30GF and PEI45GF) to improve its tensile strength, rigidity, and dimensional stability.



Equation 1

### Polyphenylene sulfide (PPS)

PPS is a semi-crystalline HPTP made from a linear structured or branched polymer. It is produced by the reaction of sodium sulfide and dichlorobenzene in a polar solvent such as N-methylpyrrolidone and at a temperature of ~ 250 °C (Equation 2). PPS can be processed using both injection moulding and compression moulding. It has excellent mechanical and electrical properties and is very resistant to high temperature, and chemical corrosion making it an ideal material for harsh environments. PPS resin is often combined with glass fiber (PPS40GF and PPS65GF) to improve its mechanical strength, thermal conductivity, dimensional stability (i.e., it retains its shape even under stress) and low-density hydrophobicity[36].

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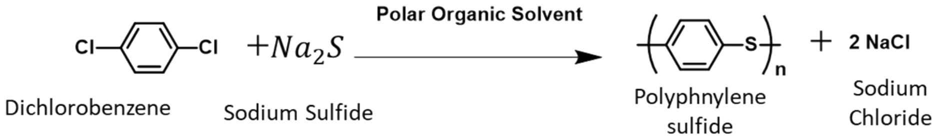
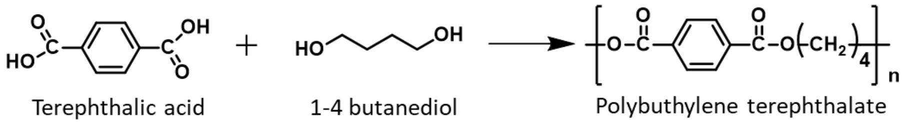


**Equation 2**

**Polybutylene Terephthalate (PBT)**

PBT is a semi-crystalline, high-performance thermoplastic produced by polycondensation of terephthalic acid and 1-4 butanediol in the presence of a catalyst like titanium butoxide or organo-zinc compound (Equation 3). The polymer consists of long chain formed through ester bonds. These bonds provide the material with durability and thermal resistance which makes it ideal for tough environments. The resulting polymer can then be further processed into different grades of PBT for specific applications. PBT (like both PEI and PPS) can be injection molded, extruded, and blow-molded making it suitable for creating complex shapes and components. PBT resin can be reinforced with different glass fiber contents (PBT30GF and PBT45GF) to improve its mechanical and thermal properties.



**Equation 3**

**Life cycle assessment (LCA) of HPTPs**

LCA is a commonly used method to evaluate the environmental performance of products and systems[37]. A process-based LCA was used in this study to evaluate the cradle-to-gate environmental plastics of three HPTPs and associated glass-fiber grades (HPTP composites). The LCA was carried out following the ISO standard [38] and according to the ISO standard, a typical LCA has four steps: goal and scope, inventory analysis, impacts assessment, and interpretation. Their application in the context of this study is described in detail below

**Goal and scope definition**

As mentioned in the introduction section, the goal of this LCA was to assess the environmental impacts resulting from the production of three selected HPTPs and associated glass fiber grades, and to identify the hotspots in the production of these HPTPs. The function of a HPTP is to serve as a high-performance polymer material with specific thermomechanical properties in the manufacturing of high-tech devices for the aerospace, automotive or electronic industries. The functional unit is the production of a certain amount of HPTP materials or HPTP composites, thus, the reference flow was 1 kg of HPTP and 1 kg of glass-filled HPTP.

**System boundaries and functional unit**

A cradle-to-gate system boundary was adopted and we considered all processes from raw material extraction through production of HPTPs, transport and storage at the warehouse. A simplified overview of the system boundary is shown in Fig. 1. No significant cut-off was assumed, so all relevant inputs for the production of HPTPs were considered. We included the consumption of raw materials, energy, water and chemicals used in the formulation of HPTPs and HPTP composites. We also accounted any solid or liquid waste from the production system. Additives including plasticizers, stabilizers, colorants and flame retardants are often added to HPTPs to improve its color, strength, resistance to heat or UV radiation and flexibility. But the addition of additives was excluded from this study due to lack of data and because it was not possible to know the desired properties of the final products. The use-phase of HPTP and HPTP composites as well as its end-of-life were excluded from the analysis because *(i)* it is not feasible to attribute the impacts of use phase to a single application of HPTPs *(ii)* the end-of life impacts can vary widely depending on the method of disposal (landfill, recycling, incineration). Capital equipment such as buildings, machineries, pipelines, and construction of the chemical factories were also excluded from the analysis as they represent a minor fraction of the overall environmental impacts. The energy use for space conditioning, lighting, and other overhead activities is not expected to make a significant contribution to total energy used for the manufacturing of HPTPs or HPTP composites, and so it was excluded from the analysis. The geographical boundary is France for the production of HPTPs and Europe for the production of raw materials, and the temporal scope is 2025 onward with relevant developments foreseen in the near future (2-5 years). The majority of the data used in the modelling is from Europe. In cases where it was necessary to use data from other continents,

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these data were adapted to the extent possible to represent the French and European practices. The electricity used in the manufacturing of HPTPs and HPTP composites was based on the power grid mix in France in 2025, while the supply of process steam and heat use was assumed to come from a highly efficient natural gas boiler.

**Life cycle inventory (LCI)**

To build the life cycle model, we established the life cycle inventory which consisted of foreground and background data. The datasets used in this study included data compiled from industrial surveys and additional data (i.e., secondary data) gathered from LCA databases such as Ecoinvent, government and organisation databases, and the literature. Due to the non-disclosure agreement, survey data from industrial companies are not publicly available, but aggregated data are provided in Tab. 1-3. The collected secondary data were adapted to French situation/practices. Where no industrial or lab data exist, a stochiometric calculation, using synthesis reaction found in scientific articles were necessary to establish the mass balance. To reflect the methods used to process HPTPs and a wide range of HPTP products, heigh processing techniques were studied. These techniques included compounding, fiber extrusion, film extrusion, profile extrusion, compression molding, rotational molding and thermoforming. The specific energy consumption (electricity, heat, and steam) of each of the processing technology used in this study is given in Tab. 4. Processing techniques such as reaction injection, transfer molding, blow molding were not evaluated because of the lack of data.

**HPTP manufacturing**

The manufacturing of HPTPs and HPTP composites starts with the extraction of fossil fuels, primarily crude oil and natural gas (Fig 1). Once extracted, crude oil and natural gas undergo various refining processes where they are transformed into monomers, the building blocks of HPTPs[39]. The produced monomers are subsequently polymerized, forming long chains of molecules, which are then processed into various HPTP products and HPTP composites through different processing techniques (e.g., molding, extrusion, thermoforming, compounding), depending on the final application of HPTPs. Prior to processing, glass fiber in different proportions may be added to the polymer matrix to obtain glass-fiber reinforced HPTPs or HPTP composite. The proportion of the added glass fiber will depend of the final application and the desired properties of the HPTP composites. We assumed 30% and 45% glass fiber addition to PEI to produce the reinforced PEI grades (PEI30GF, and PEI40GF). For the reinforced PPS grades (i.e., PPS40GF and PPS65GF) addition of 40% and 65% wt. glass fiber was considered while for the PBT composite (i.e., PBT30GF and PBT45GF), the assumed glass fiber content was and 30% and 45 % wt. The inventory data for materials, chemicals and energy consumed for the manufacturing of HPTP and their associated glass-fiber grades were based on supplier information (Tab. 1-3). As mentioned above, use of additives like flame retardants was not considered in this analysis. After manufacturing, the HPTPs and HPTP composites are transported to the warehouse where they are temporarily stored prior to their distribution to the global market. We assumed that the produced HPTPs (PEI, PPS and PBT) and their reinforced grades (PEI30GF, PEI45GF, PPS40GF, PPS65GF, PBT30GF and PBT45GF) are transported by trucks over a distance of 130 km to the warehouse. A sensitivity analysis is conducted to check the influence of transport distance on the results of LCA.

**Multifunctional processes**

The production of PEI PPS and PBT results in co-products. Economic allocation was used to split the environmental burdens between the main products (i.e., PEI, PPS, PBT) and their respective coproducts. Price of PEI (1,95 € kg$^{-1}$), PPS (1,65 € kg$^{-1}$), and PBT (2.40 € kg$^{-1}$) and that of their respective co-products notably nitric acid (0.32 € kg$^{-1}$), sodium chloride (0.22 € kg$^{-1}$), and methanol (0.65 € kg$^{-1}$) were used to carry-out the allocation (Tab. 5). The same procedure was used to perform the allocation of the glass-filled PHTPs (i.e., PEI,30GF, PEI45GF, PPS40GF and PPS65 GF, and PBT30GF and PBT45GF). Allocation in the background processes relied on the allocation method used in the Ecoinvent database [40]. To evaluate the influence of the chosen allocation approach on the results of this study, the mass allocation was also tested in the sensitivity analysis.

**Life cycle impact assessment (LCIA)**

Environmental impacts were quantified using the IMPACT World+ midpoint method [41]. This method was chosen for its wide coverage of impacts categories. Four impacts categories namely: non-renewable energy (NRE) consumption, climate change, freshwater eutrophication and terrestrial acidification were selected based on their relevance to the LCI of HPTPs and HPTP composites. For the climate change impact, contributing elementary flows are characterized using factors reported by the Intergovernmental Panel on Climate Change (IPCC) in 2014 with a 100-year time horizon[42].

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DOI: 10.1039/D5SU00615E

**Sensitivity/uncertainty analyses**

To test the robustness of the results, a number of sensitivity analyses on key inputs, assumptions, and modelling choices were carried-out. To this end, we doubled the transport distance, and varied the energy (electricity, heat and steam) used as well as water consumed during the production of HPTPs by ± 20 %, and assess the influence of these changes on the results of the study. With regard to sensitivity on the chosen allocation method (i.e., the economic allocation), we considered the mass-based allocation as an alternative allocation method and evaluate the influence of such choice on the results. Finally, the sensitivity on the selected characterisation model was assessed by selecting the CML-IA method [43] as an alternative characterisation model to the IMPACT World + method [41].

**Modelling of LCA**

The LCA of HPTP resins was modelled in Simapro 9.5.0.2 software [44] using mainly European LCI database. The main advantage of the Simapro tool is that it contains several available databases such as the Ecoinvent [40] and it has the ability to produce and evaluate results. The results from the Simapro software highlights the estimated environmental performance in terms of GHG emission, resource and energy consumption, eutrophication/acidification, and various other environmental impacts (not included in our study).

## Results

### Non-renewable energy (NRE) consumption

We report here the estimates of environmental impacts of production of three HPTP and associated reinforced glass-fiber grades, under different processing technologies. The non-renewable energy (NRE) consumption ranged from 247.6 – 370.3 MJ kg$^{-1}$for the unfilled PEI, while it varied from 209.5 – 322.2 MJ kg$^{-1}$ for PEI30GF and from 187.9 – 295.1 MJ kg$^{-1}$for PEI45GF, depending of the processing technology (Fig. 2a). The lowest value of NRE consumption value was related to the compounding process while the highest corresponded to the thermoforming process. Indeed, thermoforming involves more ancillary equipment and thus consumed more electrical energy than the compounding or the film extrusion processes (Tab. 4). The low embodied energy of glass fiber together with the reduction of feedstock/chemicals needed for the polymer matrix led to the overall low NRE consumption of glass-fiber grades (PEI30GF, PEI45GF) relative to the unfilled PEI (Fig. 2a). The contribution analysis revealed that the feedstocks (methaphenylene diamine, bisphenol A) used in the manufacturing of PEI and its associated grades (PEI30GF and PEI45GF) were the main contributors (43% -55%) to the total NRE consumption, followed by processing energy (43%-49%), glass fiber (0 – 6%) and to a lesser extend the solvents or chemicals (NaOH, nitric acid) used during manufacturing (1 -1.5%) and transport (0.11% - 0.16%) (Fig 2b). Most of these impacts originated from fossil crude oil and natural gas used in the production of feedstocks/chemicals necessary for the manufacturing of PEI and associated glass-filled grades. The majority of NRE consumption is in the form of fossil fuels use to produce the intermediate chemicals and monomers used in PEI production.

For the PPS, the NRE consumption varied between 103.3 and 183.1 MJ kg$^{-1}$, while it ranged from 80.9 – 148.6 MJ kg$^{-1}$for the PPS40GF, and from 65.5 – 124.8 MJ kg$^{-1}$ for the PPS65GF (Fig. 3a). The patterns of NRE consumption for PPS were similar to those of PEI, with the total NRE consumption decreasing when glass fiber was added to the polymer matrix. A breakdown of the total NRE energy consumption showed that feedstocks (i.e., P-dichlorobenzene, sodium sulfide) were the major contributors to NRE consumption (40% – 70%), followed by energy used during processing (30% – 34%), glass fiber (0% - 25%) and transport (0.3% – 0.6%) as shown in Fig. 3b. The trends observed here (PPS > PPS40GF > PPS65GF) were similar to that observed in the PEI case (Fig. 3a).

The NRE consumption ranged from 101.6 – 115.1 MJ kg$^{-1}$ for the PBT, while that of its glass-filled grades ranged from 84.6 - 94.2 MJ kg$^{-1}$for PBT30GF and from 76.5 – 84.6 MJ kg$^{-1}$for PBT45GF (Fig 4a). Here also, the total NRE consumption decreased as the glass fiber content of glass-filled PBT increases. Feedstock/materials (terephthalic acid, Butane 1,4 diol and titanium butoxide) used in the manufacturing of BPT were the main contributors to the total NRE consumption (59% – 73%), followed chemicals (16% – 17%), glass fiber (0% – 17%) and process energy (5% – 6%). The contribution of transport remained very low as in the case of PEI and PPS (Fig 4b). Overall, these results showed that the production of HPTPs has the potential to deplete fossil fuel resources (Fig. 2– 4).

### Climate Change

The GHG emissions ranged from 12.4 – 16.5 kgCO$_{2eq}$ kg$^{-1}$for the PEI while for the glass reinforced grades the GHG emissions varied from 10.7 – 14.5 kgCO$_{2eq}$ kg$^{-1}$ for the PEI30GF, and from 9.9 – 13.2 kgCO$_{2eq}$ kg$^{-1}$for the PEI45GF (Fig. 2c), depending on the processing technology. The high estimate of GHG emissions was related to thermoforming, while the low estimate was associated to the

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DOI: 10.1039/D5SU00615E

compounding process. We also noted that GHG emissions decreased when PEI was reinforced with 30% or 45% glass fiber (PEI30GF and PEI45GF) (Fig 2c). Here as well, feedstocks were the main contributors (42 – 54%) to the total GHG emissions of PEI and associated glass-fiber production, followed by the process energy (43% – 47%%), glass-fiber (0% – 8%), chemicals including NaOH (1.5% – 2%), direct emissions (0.08 – 0.1%), transport (0.14% – 0.21%), and water (< 0.1%) contributed minorly to GHG emissions of PEI and associated reinforced grades (Fig. 2d).

For the PPS, the total GHG emissions ranged from 6.9 – 8.6 kgCO$_{2eq}$ kg$^{-1}$while they varied from 5.3 – 6.8 kgCO$_{2eq}$ kg$^{-1}$for the PPS40GF and from 4.2 – 5.6 kgCO$_{2eq}$ kg$^{-1}$for the PPS65GF (Fig 3c). Reinforcing PPS with glass-fiber resulted to decreasing GHG emissions. The GHG emissions of PPS were also much lower than those of PEI because PPS was less-energy intensive to manufacture than PEI. Similar to PEI, the breakdown of the total GHG emissions showed that feedstock (37% – 60%) largely dominated the total GHG emissions of PPS, followed by glass fiber (0% – 32%), direct emissions (17% – 27%), the process energy (12% – 14%), and transport (0.3% – 0.5%) (Fig 3d).

The GHG emissions ranged from 4.5 – 5.1 kgCO$_2$ kg$^{-1}$ for PBT, 4.0 – 4.4 kg CO$_2$ kg$^{-1}$ for PBT30GF and from 3.7 – 4.1 kg CO$_2$ kg$^{-1}$ for PBT45GF, depending on the processing technologies (Fig. 4c). The lower GHG emission values were associated with both compounding and film extrusion while the highest GHG emissions were linked to thermoforming processes. But unlike with PPS, direct GHG emissions from manufacturing were very low (< 0.5 %) for PBT and its associated glass-filled grades. The GHG emissions also showed a decreasing trend with increasing glass-fiber content of PPS. The major contributors to GHG emissions were again feedstocks (41% – 56%), followed by chemicals (26% – 37%), glass fiber (0% – 27%) process energy (4% – 6%) and transport (0.5 – 0.7%) (Fig 4d). Overall, these findings highlighted the impact of feedstocks, chemicals, and processing technologies on the carbon footprint of HPTPs (Fig. 2 – 4). We noted that HPTPs of amorphous group (PEI) were more energy and carbon intensive than the crystalline ones (i.e., PPS and PBT).

**Freshwater eutrophication (EP)**

Freshwater eutrophication (EP) occurs when nutrients such as phosphates are introduced to surface water causing the rapid growth of aquatic plants. The EP varied from $3.1\cdot10^{-4}$ – $3.5\cdot10^{-4}$kg PO$_4^{3-}$ kg$^{-1}$for PEI, $2.4\cdot10^{-4}$ – $2.9\cdot10^{-4}$ kgPO$_4^{3-}$ kg$^{-1}$ for PEI30GF and from $2.1\cdot10^{-4}$ – $2.5\cdot10^{-4}$ kg PO$_4^{3-}$kg$^{-1}$ for PEI45GF (Fig 5a), depending on the processing technologies. Again, the high estimate value is related to thermoforming while the low one is linked to compounding. The EP impact decreased with the increase in glass-fiber content of PEI Most of these emissions were direct emissions (53% – 56%) originating from the manufacturing of PEI and associated glass fiber, followed by feedstock emissions (31% – 36%), process energy (9% - 11%) glass-fiber (0 – 1.2%), and transport (< 1%) (Fig. 5b). The main pollutants contributing to EP were biochemical oxygen demand (BOD), chemical oxygen demand (COD) and dissolved organic carbon (DOC) were the main pollutants of contributing to freshwater EP of PEI.

Estimates of EP ranged from $3.41\cdot10^{-4}$– $3.43\cdot10^{-4}$kg PO$_4^{3-}$ for the PPS, while they varied from $3.16\cdot10^{-4}$– $3.18\cdot10^{-4}$kg PO$_4^{3-}$ for PPS40GF and from $3.32\cdot10^{-4}$ – $3.34\cdot10^{-4}$kg PO$_4^{3}$ for the PPS65GF, depending on the processing technology (Fig 6a). The patterns were similar to those observed in other impact categories (i.e., PPS > PPS40GF>PPS65GF). Contribution analysis showed that feedstocks/materials (P-dichlorobenzene, sodium sulfide) dominated (97 – 99%) the EP impacts for PPS and associated glass fiber (PPS40GF and PPS65GF), followed by glass fiber (0% – 0.8%), process energy (0.3 – 0.5%), direct emissions (0.2% – 0.3%) and transport (< 0.1) (Fig 6b). Waterborne emissions (COD, BOD, DOC and Phosphate) were the main pollutants contributing to EP. Freshwater EP were an order of magnitude higher for PPS relative to PEI.

The freshwater EP ranged from $3.17\cdot10^{-4}$– $3.22\cdot10^{-4}$kg PO$_4^{3-}$ kg$^{-1}$for PBT, while it varied from $2.3\cdot10^{-4}$ – $2.4\cdot10^{-4}$ kg PO$_4^{3-}$ kg$^{-1}$ for PBT30GF and from $1.98\cdot10^{-4}$ – $2.01\cdot10^{-4}$kg PO$_4^{3-}$kg$^{-1}$ for PBT45GF, depending on processing technologies (Fig. 7a). As in previous cases, the high estimate of EP was related to thermoforming, while the low estimate was linked to compounding. The EP decreased with increasing glass-fiber content. However, the differences in estimates of EP between these HPTPs were very small. The top contributors to freshwater EP for PBT and its associated glass-filled grades were feedstocks (88 – 92%), followed by chimicals (3 – 4%), direct emissions (2% – 3 %), glass-fiber (0% –4%), and process energy (0.7 – 0.8%) (Fig. 7b). Here the main pollutants contributing to this impact were BOC, COD, phosphate and phosphorus. The EP of amorphous HPTP (PEI) was comparable to that the semi-crystalline HPTPs (PPS and PBT).

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**Terrestrial Acidification (AP)**

Terrestrial acidification (AP) impact is the result of atmospheric deposition of emitted pollutants and their subsequent deposition on soil and water, leading to decrease in plant performance, biodiversity losses and damage to infrastructure. Terrestrial AP ranged from $8.6\cdot10^{-5}$ – $1.1\cdot10^{-4}$ kg $SO_2$ kg$^{-1}$ for PEI while it varied from $7.6\cdot10^{-5}$ – $9.7\cdot10^{-5}$ kg $SO_2$ kg$^{-1}$ for PEI30GF and $7.1\cdot10^{-5}$ – $9.1\cdot10^{-5}$ kg $SO_2$ kg$^{-1}$ for PEI65GF, depending on the processing technologies (Fig. 5c). The lowest estimate of AP impacts was associated with compounding and the highest related to the thermoforming. The patterns of AP also followed that observed in other impacts with increasing glass-fiber content leading to lower EP impacts. The largest part of AP impacts came from feedstocks/materials (47% – 63%), followed by processing energy (33% – 36%) and glass-fiber (0 % – 15%), chemicals (2% – 3%) and transport to a lesser extent (Fig. 5d).

For the PPS, estimates of terrestrial AP ranged from $4.7\cdot10^{-5}$– $5.7\cdot10^{-5}$ kg$SO_2$ kg$^{-1}$ for PPS, whereas they varied from $4.1\cdot10^{-5}$– $4.9\cdot10^{-5}$ kg $SO_2$ kg$^{-1}$ for PPS40GF and $3.7\cdot10^{-5}$ – $4.5\cdot10^{-5}$ kg $SO_2$ kg$^{-1}$ for PPS65GF, depending on the processing technologies (Fig. 6c). As in the previous cases, the increased in glass-fiber content led to lower AP for glass-filled PPS relative to unfilled PPS. The top process contributors to AP impacts were feedstock/materials (43% - 89%), glass fiber (0% – 47%) and process energy (9% – 10%) (Fig 6d). Pollutants contributing to AP impacts were ammonia ($NH_3$), nitrogen oxides ($NO_x$), sulphur dioxide ($SO_2$) and sulphate.

Finally, for the PBT, estimates of AP varied from $3.7\cdot10^{-5}$ – $4.0\cdot10^{-5}$ kg$SO_2$ kg$^{-1}$ for PBT, while they ranged from $3.6\cdot10^{-5}$– $3.8\cdot10^{-5}$ kg $SO_2$ kg$^{-1}$ for PBT30GF and $3.5\cdot10^{-5}$– $3.7\cdot10^{-5}$ kg$SO_2$ kg$^{-1}$ for PBT45GF, depending on the processing technologies (Fig 7c). A breakdown of AP impacts showed that feedstock (32% – 49%) was the most contributing process followed by the catalyst (29% – 47%), glass fiber (0 – 37%), process energy (2% – 4%) and transport (0.6% – 0.7%) (Fig 7d). The primary pollutants contributing to these impacts included $NO_x$ and $SO_2$. The AP impacts of both PBT and PEI an order of magnitude lower than those of PPS. Overall, our analysis suggest that depletion of non-renewable resources and climate change are the most concerning environmental impact categories in the life cycle of HPTP, mainly due to petroleum derived-feedstocks (i.e., monomers) used for their formulation and the processing energy. No trade-offs in environmental categories were observed in this study and the ranking of HPTPs were maintained in all cases.

**Sensitivity Analysis**

The results of the sensitivity analysis are presented in Fig. 8. Because of the very small change in EP and AP impact categories only the data for NRE consumption and climate change are displayed. As shown in Fig. 8, the scenario with the highest influence were related to model assumptions (i.e., allocation method, impacts assessment method), which caused variation of 3% to 58% in both the NRE consumption and climate change impact categories, depending on the type of HPTP. Process energy (6% – 16%) was the input that affected the most in both impacts categories (i.e., NRE consumption and Climate change). Transportation (< 0.4% change in energy use and GHG emissions) and water use (<0.1% change in both impacts categories) seemed to have the least significant influence on the results (Fig. 8a-b). In all scenarios the trends and ranking of environmental impacts the two groups of HPTPs (i.e., PEI > PPS > PBT) remained unchanged. Within the amorphous group PEI > PEI30GF > PEI45GF while in the crystalline group PPS > PPS40GF > PPS65GF and PBT > PBT40GF > PBT45GF (Fig 8 a–b).

**Discussion**

The growing used of HPTPs is significantly impacting the environment, resulting in contamination of surrounding environments. Addressing HPTP pollution is not just about cleaning-up the waste, it involves understanding its origins, the scale of its production, consumption habits and its end-of-life management practice globally. We contributed to this effort by studying the environmental impacts of the three HPTPs (PEI, PPS and PBT) and their respective reinforced glass-fiber grades (PEI30GF, PEI45GF; PPS40GF, PPS65GF; PBT30GF and PBT45GF). We showed that feedstocks and processing energy were the main sources of environmental impacts in all cases (Fig. 2–4). Our study also corroborated recent conclusions that feedstocks and process energy are the main hotspots of plastic/polymer manufacturing[16,45]. The low contribution (<1%) of transport to NRE consumption and GHG emissions of HPTPs in our study is line with the assumed short distance covered (130 km round-trip). Some authors report up to 8 % contribution of transport to GHG emissions of plastics[46], but a recent study suggests that their contribution to total GHG emissions of plastics would remain negligible (< 3%)[34,47] in line with findings of this study. Very few LCA on HPTPs exist in the literature, however, studies on commodity plastics show conclude that the production of virgin commodity plastics requires 54 -200 MJ kg$^{-1}$ [48]. Our data showed that HPTP required 76 – 370 MJ kg$^{-1}$, which is 1.4 – 1.8 times higher than the reported ranges for commodity plastics. With regard to GHG emissions, our average GHG emissions estimate 14.1 kg$CO_{2eq}$ kg$^{-1}$ for PEI of agreed well with the climate change value of PEI (11 kg$CO_{2eq}$ kg$^{-1}$)

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reported by Bachmann et al.[14]. The CONVENA group reported an estimate of 5.1 kg $CO_{2eq}$ $kg^{-1}$ for the virgin glass-fiber reinforced PPS[49], which compared well with the average value of GHG emissions (7.6 kg $CO_{2eq}$ $kg^{-1}$) for PPS found in this study. For PBT available literature reports a cradle-to-gate GHG emissions of 6.2 kg $CO_{2eq}$ $kg^{-1}$ [48] in agreement with the average 4.7 kg $CO_{2eq}$ $kg^{-1}$ for PBT in this study. A recent literature review on environmental impacts of seven commodity plastics (incl. HDPE, LDPE, PC, PET, PP, PS and PVC) reported that GHG emissions of these plastics range from 1.4 – 4.8 kg $CO_{2eq}$ $kg^{-1}$, depending on the plastic types[48]. These values are only 2 – 4 times lower than those of PPS found in this study, but they are much lower (4 – 9 folds) than those of PEI, suggesting that GHG emissions of HPTPs are much higher than those of commodity plastics. The high GHG emissions of HPTPs relative to most commodity plastics can be explained by their superior qualities, which often make them difficult to process, thus necessitating specialized and high energy consuming machinery. Additives such as plasticizers are used in the manufacturing of HPTP products [2,50,], but they were not included in this study due to lack of data. Some of these additives are energy-intensive and potentially harmful to human and/or the environment [51–54]. Consequently, the reported estimates of total NRE consumption and GHG emissions in this study can be viewed as conservative. Effective ways to reduce the environmental impacts of manufacturing HPTPs would be *(a)* to improve energy efficiency in HPTP production, *(b)* switch to less $CO_2$-intensive fuels and materials, *(c)* use carbon capture and storage (CCS) or utilisation (CCU) technologies, and *(d)* to recycle or use recycled material in HPTP production. Improving energy efficiency in production processes can significantly reduce energy use and $CO_2$ emissions of HPTPs[55]. This can be achieved by replacing outdated installations with energy-efficient ones, upgrading current process, installing heat recovery technologies and power recovery expanders, optimising heat integration, or by implementing cogeneration units in current HPTP production processes [11,56,57]. But, the potential of energy efficiency in HPTP industries is limited because it requires a significant financial commitment. Switching to renewable and/or low carbon feedstock and energy carriers (e.g., biomethane, hydrogen, liquid biofuel) is another carbon mitigation strategy in HPTP industries. This strategy can reduce up to 85% direct $CO_2$ emissions in HPTP production[58,59] . Biobased xylene could substitute phthalic anhydride in PEI production [13,14,60,61]. Likewise, lignin-based vanillin can serve as platform chemicals for the production of biobased substitute to bisphenol A in PEI production [62,63]. However, each of these alternatives come with high energy penalty[62] and most of these platform chemical technologies are not yet mature enough to fully switch to $CO_2$ neutral feedstocks or energy sources.

Carbon capture and storage (CCS) or utilisation (CCU) is another strategy being widely explored in HPTP industries for the management of direct $CO_2$ emissions from HPTP manufacturing processes. Depending on capture technology, CCS can remove 80-90% direct $CO_2$ emissions from HPTP manufacturing processes[59,63]. The captured $CO_2$ can also be used as renewable feedstock in the production of monomers/components necessary for the manufacturing of HPTP [64,65]. However, our data showed that depending on type of HPTP, direct $CO_2$ emissions represented 0% – 27% of the total GHG emissions of HPTPs (Fig 2,4,6), but most of these greenhouse gases were non-$CO_2$ pollutants. Consequently, CCS or CCU may have very limited potential in HPTP industries because of the low $CO_2$ volumes and concentrations in the HPTP production and the fact that both CSS and CCU are energy-intensive and require huge investments and expansion of infrastructure[66].

Incineration with energy recovery is a widely implemented waste management strategy in HPTP industries. Capitalising on the high calorific value of HPTP to generate useful energy in the form of heat and electricity, incineration significantly reduces the volume of HPTP waste and contribute to energy production, making it a valuable component of integrated waste management system. Its prevalence is largely attributed to these dual benefits (i.e., energy recovery and waste minimization). However, incineration is a carbon intensive process, it releases ~2.4 kg $CO_{2eq}$ $kg^{-1}$plastics[67] in addition to toxic gases (e.g., dioxine), particulate matters and volatile organic carbon[68]. Consequently, incineration may undermine the general efforts of GHG emissions reductions in HPTP industries.

Recycling is an efficient approach to reduce energy, GHG emissions and other environmental impacts of HPTPs production [69,70] . It has been reported that recycling reduces 0.2 – 3 kg $CO_2$ $kg^{-1}$ relative to virgin plastics [71]. However, not all, HPTPs recycling pathways have better process emissions than the respective virgin HPTP value chain. Consequently, the energy and carbon reduction potential through recycling should be done on case-by-case basis. Also, the leaching of harmful pollutants (incl. hazardous chemicals) during recycling poses a significant threat[52] and may limit the mitigation potential of this strategy. Another challenge that hinders the mitigation potential of this strategy is that certain HPTPs especially those compounded with glass or carbon fiber are complex to recycle and there is a lack of market and fiscal based incentive rewarding the significant environmental and social benefits of recycling.

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## Conclusion

We conducted a detailed investigation of environmental impacts of HPTPs using LCA. We found that the feedstocks and the process energy requirement were the major contributors to the environmental impacts of HPTP production. The NRE consumption and GHG emissions of amorphous HPTPs were twice higher than those of semi-crystalline counterparts. EP and AP were low for all the investigated HPTPs. While an immediate reduction in HPTP production is difficult due to its increasing demand, strategic initiatives such as sustainable feedstock sourcing, recycling and efficiency improvement can improve its carbon footprint and significantly mitigate its negative impacts on environment. Our results provide a benchmark for comparing and improving the NRE consumption, GHG emissions, EP and AP of HPTPs. The analysis provides valuable insights into the environmental impacts HPTPs, examining the effects of processing technology and addition of glass fiber. Our findings serve as important reference for HPTP stakeholders and policy makers. We cautioned, however, that the results of this study should not be viewed as a global representative, as the case study scope was limited to France. Future work should expand our modelling framework to include other HPTPs (e.g., PEEK, PTFE, PPSU, PSU) and their glass/carbon fiber reinforced grades, the use and recycling of HPTPs in order to evaluate the environmental benefits of different mitigation strategies for HPTPs that may include these actions. We also plan to extend the modelling from national to regional scale by including regional details as improved geographic granularity could help better inform the setting of region or national goals and actions.

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## Author contributions

Aicha Touré and Sylvestre Njakou Djomo carried-out the LCA and wrote the first draft of the manuscript, which was edited and approved by all authors. Sylvestre Njakou Djomo, Jannick Duchet Rumeau, and Jeremy Sautel designed the study and data collection, Aicha Touré Bérenger Thollet and Emile Pantaleao collected the data, all authors contributed to the data analysis.

## Declaration of competing interests

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

## Data availability

All data that support the findings of study are included within the article

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**Figure legend text**

**Fig. 1:** System boundary of the evaluated HPTP products (PEI = polyetherimide, PEIGF = polyetherimide filled with glass fiber; PPS = polypropylene sulfide; PPSGF = polypropylene sulfide filled with glass fiber; PBT = polybuthylene terephthalates; PBT = polybuthylene terephthalates filled with glass-fiber)

**Fig. 2:** Non-renewable energy (NRE) consumption and GHG emissions of PEI and associated glass-fiber grades (a-b) under different processing techniques (n=8) and processes contributing to NRE and GHG emissions (c-d) of PEI and its reinforced glass fiber grades (PEI30GF and PEI45GF). Label of value less than 4% are hidden in the graphic

**Fig. 3:** Non-renewable energy (NRE) consumption and GHG emissions of PPS and associated glass-fiber grades (a-b) under different processing techniques (n=8) and processes contributing to NRE and GHG emissions (c-d) of PPS and its reinforced glass fiber grades (PPS40GF and PPS65GF). Label of value less than 4% are hidden in the graphic

**Fig. 4:** Non-renewable energy (NRE) consumption and GHG emissions of PBT and associated glass-fiber grades (a-b) under different processing techniques (n=8) and processes contributing to NRE and GHG emissions (c-d) of PBT and its reinforced glass fiber grades (PBT40GF and PBT45GF). Label of value less than 4% are hidden in the graphic

**Fig. 5:** Eutrophication (EP) and acidification potential (AP) of PEI and associated grass-fiber (a-b) under different processing techniques (n=8) and processes contributing to EP and AP (c-d) of PEI and its reinforced glass fiber grades (PEI30GF and PEI45GF). Label of value less than 4% are hidden in the graphic

**Fig. 6:** Eutrophication (EP) and acidification potential (AP) of PPS and associated grass-fiber (a-b) under different processing techniques (n=8) and processes contributing to EP and EP (c-d) of PPS and its reinforced glass fiber grades (PPS40GF and PPS65GF). Label of value less than 4% are hidden in the graphic

**Fig.7:** Eutrophication (EP) and acidification potential (AP) of PBT and associated grass-fiber (a-b) under different processing techniques (n = 8) and processes contributing to EP and EP (c-d) of PBT and its reinforced glass fiber grades (PBT40GF and PBT45GF). Label of value less than 4% are hidden in the graphic

**Fig. 8:** Sensitivity analysis of energy use (a) and GHG emissions (b) for the different studied HPTP.

**Tables list**

**Tab. 1:** Inventory data for polyetherimide (PEI) and its reinforced glass-fiber grades

**Tab. 2:** Inventory data for polyphenylene sulphide (PPS) and its reinforced glass-fiber grades

**Tab. 3:** Inventory data for polybutylene terephthalate (PBT) and its reinforced glass-fiber grades

**Tab. 4:** Specific energy consumption of HPTPs under different processing technologies

**Tab. 5:** Quantity, market value and allocation share of different HPTP

**End of the manuscript text, figure legends and Tables**

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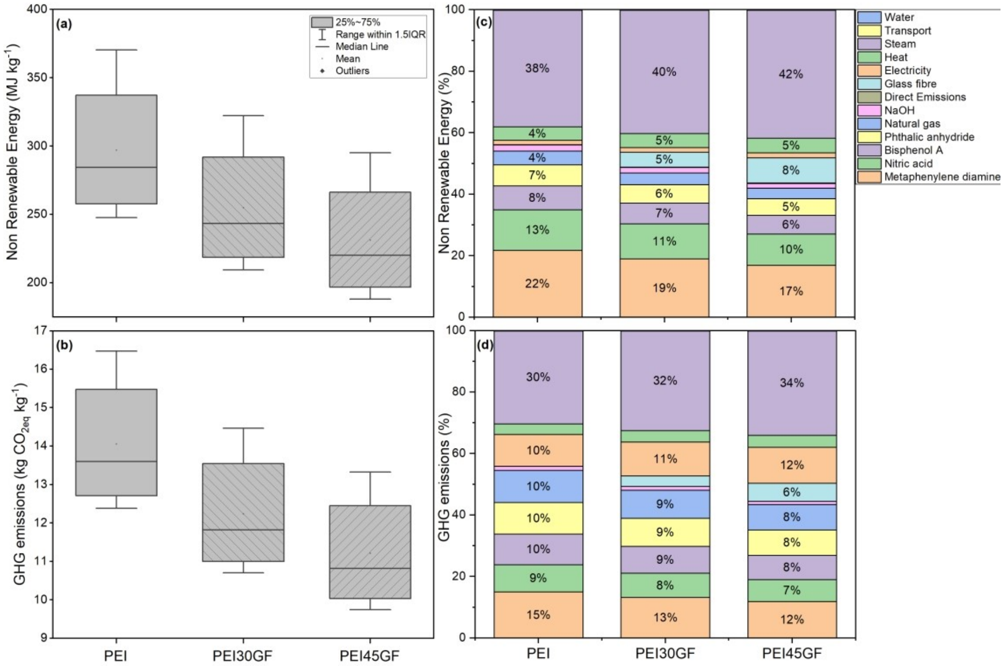

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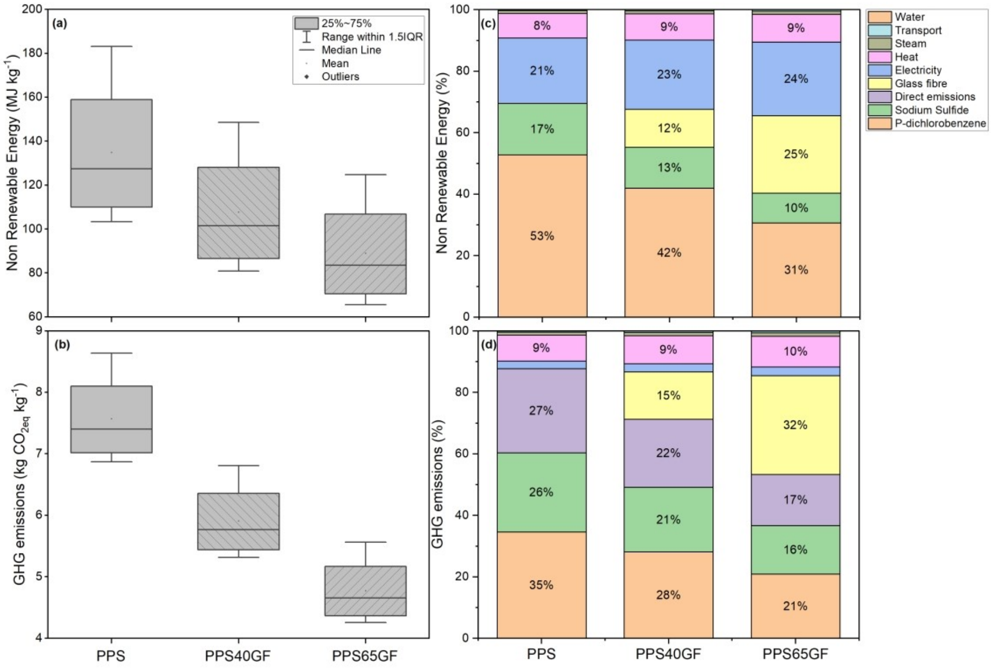

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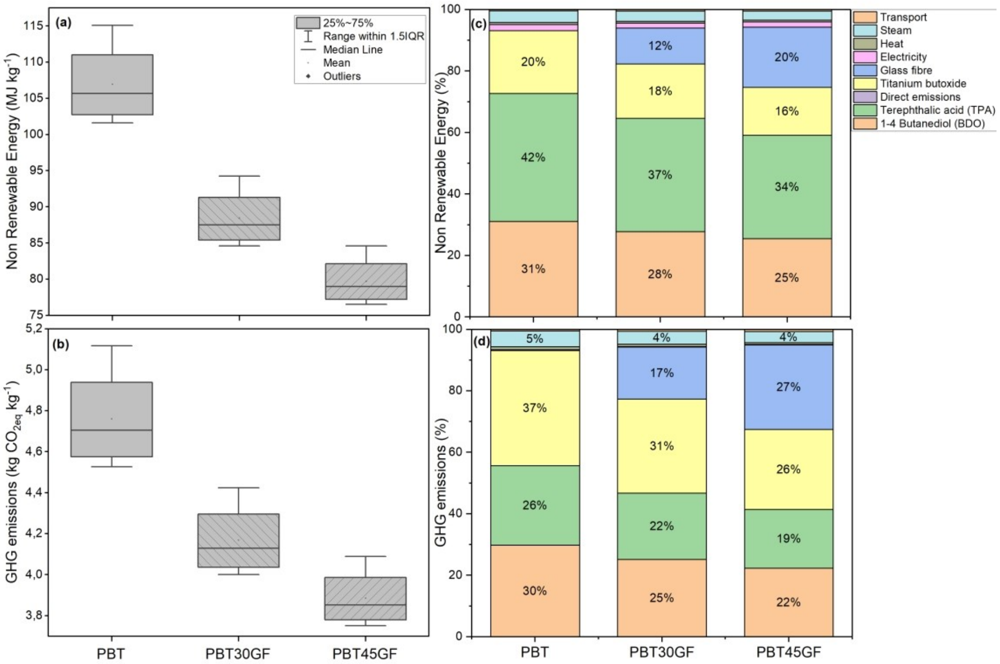

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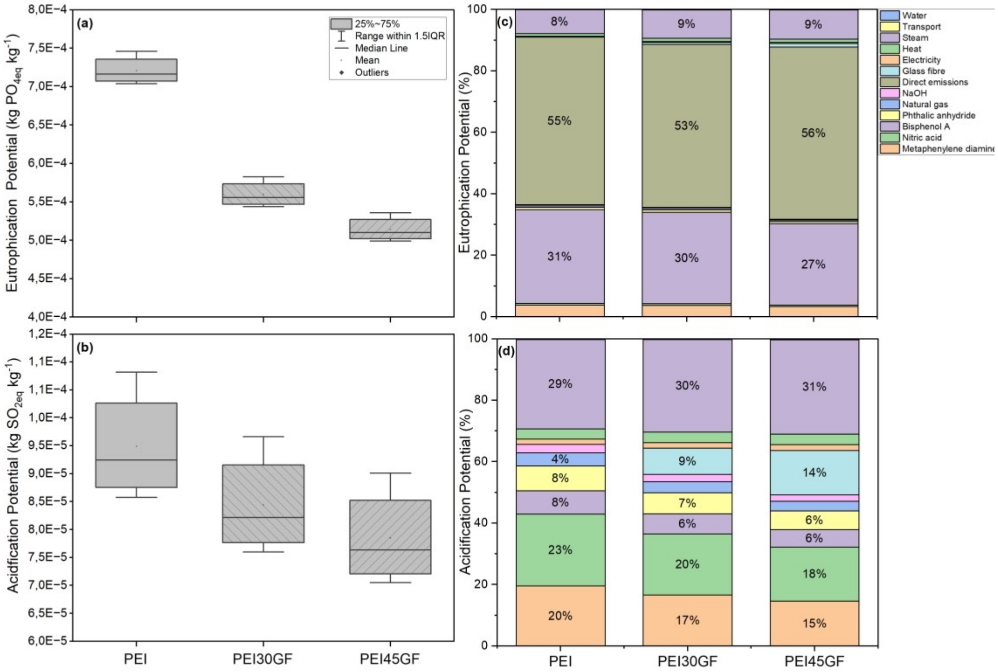

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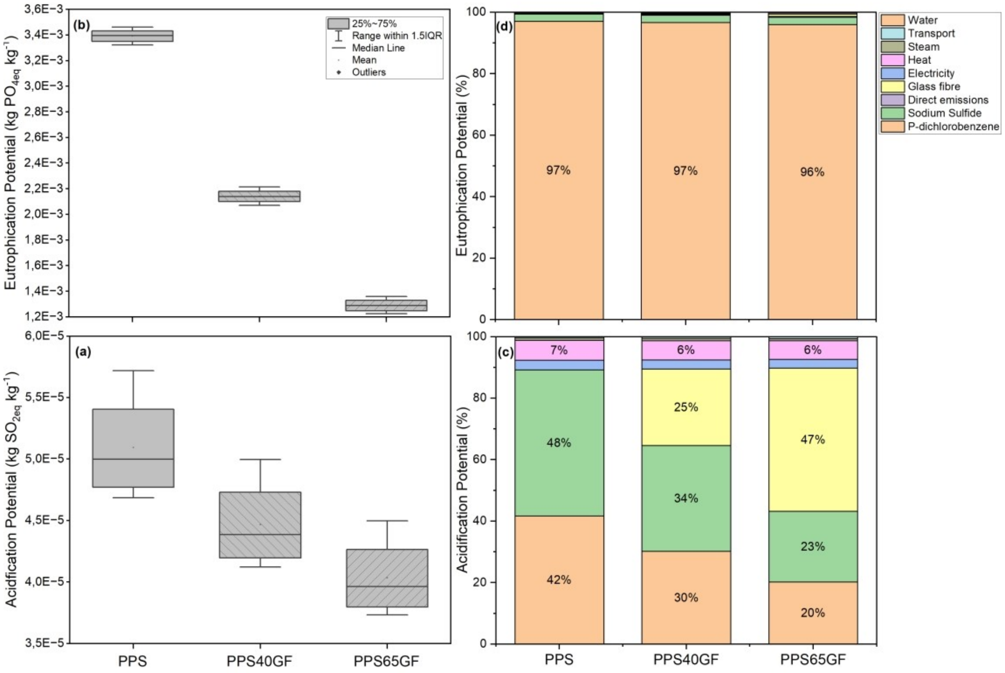

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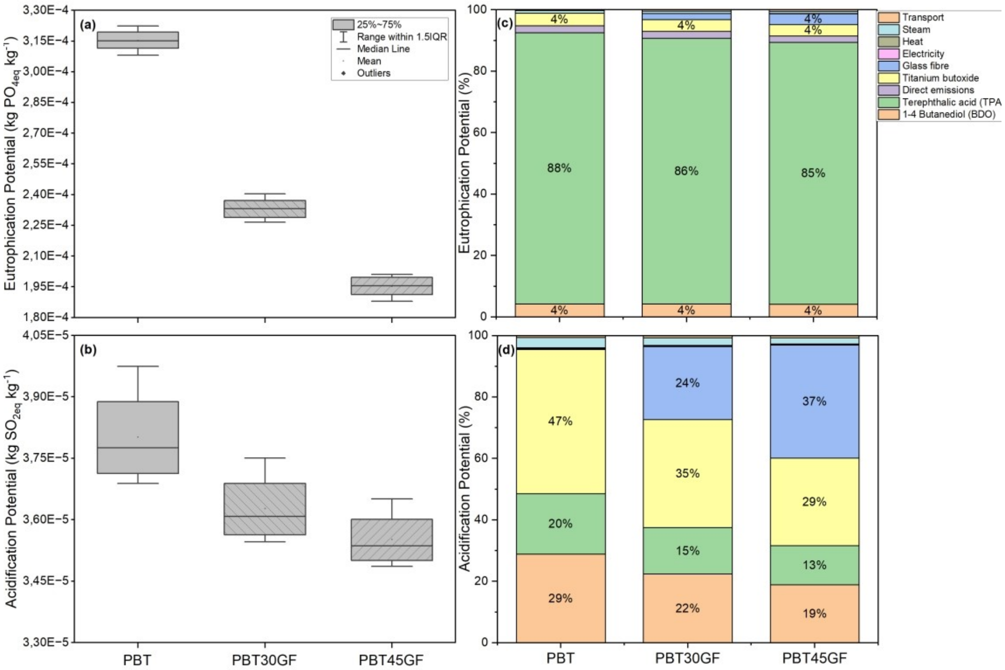

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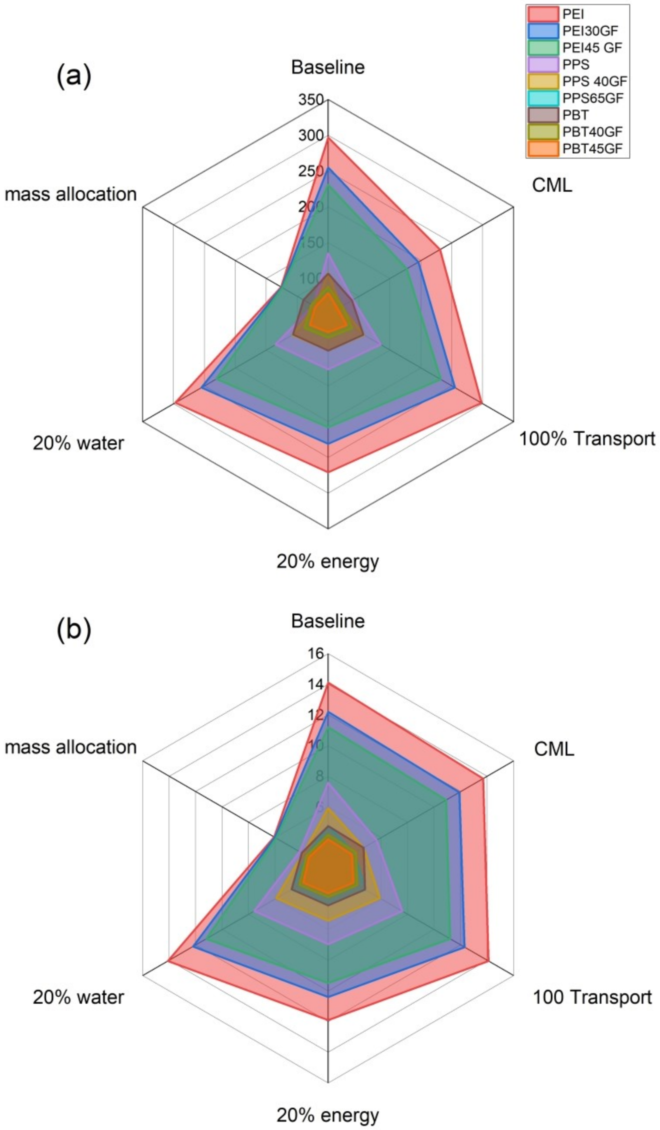

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## List and description of Tables

Table 1: Inventory data for the polyetherimide (PEI) and its reinforced glass-fibre grades

| | PEI† | PEI30%GF | PEI45%GF |
|---|---|---|---|
| ***Inputs*** | | | |
| Bisphenol A (kg) | 412 | 288 | 227 |
| Phthalic anhydride | 550 | 385 | 303 |
| Metaphenylene diamide | 192 | 135 | 106 |
| Nitric acid | 2500 | 1750 | 1375 |
| Nitrogen | 0.1 | 0.1 | 0.1 |
| Sodium hydroxide (kg) | 300 | 210 | 165 |
| Natural gas | 651 | 456 | 358 |
| Glass fiber (kg) | - | 300 | 450 |
| Electricity (kWh) | 3564 | 3030 | 2760 |
| Heat (MJ) | 7840 | 6660 | 6080 |
| Steam (kg) | 25057 | 21300 | 19400 |
| Water ($m^3$) | 732 | 512 | 403 |
| ***Outputs*** | | | |
| PEI (kg) | 1000 | - | - |
| PEI30%GF (kg) | - | 1000 | - |
| PEI45%GF (kg) | - | - | 1000 |
| Nitric acid (kg) | 2200 | 1540 | 1210 |

*†Input-Output data for the PEI were obtained from Bachmann et al.[14]*
*PEI30GF = PEI with 30% wt. glass fibre; PEI45GF = PEI with 45% wt. glass fibre*

**Table 2: I**nventory data for polyphenylene sulfide (PPS) and its reinforced glass-fibre grades

| | PPS | PPS40%GF | PPS65%GF |
|---|---|---|---|
| ***Inputs*** | | | |
| P-dichlorobenzene (kg) | 1363 | 818 | 477 |
| Sodium sulfide (kg) | 723 | 434 | 253 |
| Glass fiber (kg) | - | 400 | 650 |
| Electricity (kWh) | 2828 | 2260 | 1910 |
| Heat (MJ) | 7071 | 5660 | 4770 |
| Steam (kg) | 283 | 226 | 191 |
| Water ($m^3$) | 750 | 750 | 750 |
| ***Outputs*** | | | |
| PPS (kg) | 1000 | - | - |
| PPS40%GF (kg) | - | 1000 | - |
| PPS65%GF (kg) | - | - | 1000 |
| Sodium chloride (kg) | 1086 | 651 | 380 |

*PPS40GF = PBT with 40% wt. glass fibre, PPS65GF = PBT with 65% wt. glass-fibre*

**Table 3: I**nventory data for polybutylene terephthalate (PBT) and its reinforced glass-fibre grades

| | PBT | PBT30GF | PBT45GF |
|---|---|---|---|
| ***Inputs*** | | | |
| Terephthalic acid (kg) | 880 | 630 | 514 |
| Butana 1,4 diol (kg) | 409 | 296 | 242 |
| Titanium butoxide (kg) | 40 | 28 | 22 |
| Glass fiber (kg) | - | 300 | 450 |
| Electricity (kWh) | 189 | 132 | 123 |
| Heat (MJ) | 1581 | 1107 | 870 |
| Steam (kg) | 912 | 638 | 502 |
| ***Outputs*** | | | |
| PBT (kg) | 1000 | - | - |
| PBT30%GF (kg) | - | 1000 | - |
| PBT45%GF (kg) | - | - | 1000 |
| Methanol (kg) | 290 | 208 | 169 |

*PBT30GF = PBT with 30% wt. glass fibre, PBT45GF = PBT with 45% wt. glass-fibre*

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**Table 4**: Specific energy consumption of high-performance plastics (HPTPs) under different processing technologies

| Processing technologies | Polyetherimide (PEI) | | | Polyphenylene sulfide (PPS) | | | Polybutylene terephthalate (PBT) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Electricity (kWh $kg^{-1}$) | Heat (MJ $kg^{-1}$) | Steam (kg $kg^{-1}$) | Electricity (kWh $kg^{-1}$) | Heat (MJ $kg^{-1}$) | Steam (kg $kg^{-1}$) | Electricity (kWh $kg^{-1}$) | Heat (MJ $kg^{-1}$) | Steam (kg $kg^{-1}$) |
| Compounding | 0.80 | 1.75 | 20.16 | 0.63 | 1.52 | 0.08 | 0.54 | 1.34 | 0.06 |
| Fibre extrusion | 1.07 | 2.36 | 20.83 | 0.85 | 2.12 | 0.11 | 0.72 | 1.81 | 0.09 |
| Film extrusion | 1.70 | 3.73 | 21.28 | 1.35 | 3.64 | 0.16 | 1.14 | 2.86 | 0.14 |
| Profile extrusion | 1.89 | 4.17 | 22.40 | 1.51 | 3.76 | 0.18 | 1.28 | 3.20 | 0.15 |
| Injection moulding | 3.93 | 8.64 | 24.86 | 3.12 | 7.73 | 0.37 | 2.65 | 6.63 | 0.32 |
| Compression moulding | 3.99 | 8.78 | 28.90 | 3.17 | 7.92 | 0.38 | 2.69 | 6.73 | 0.32 |
| Rotational moulding | 7.34 | 16.16 | 30.11 | 5.83 | 14.57 | 0.70 | 4.95 | 12.38 | 0.59 |
| Thermoforming | 7.79 | 17.13 | 31.92 | 6.18 | 15.45 | 0.74 | 5.25 | 13.13 | 0.63 |
| Average | 3.56 | 7.84 | 25.06 | *2.83* | *7.07* | 0.34 | 2.41 | 6.01 | 0.29 |

**Table 5: Q**uantity, market values, and allocation shares of HPTPs

| Product and co-products | Quantity (kg) | Price (€ $kg^{-1}$) | Total costs (€) | Share (%) |
|---|---|---|---|---|
| Polyetherimide (PEI) | 1000 | 1.95 | 1950 | 74 |
| Nitric acid | 2200 | 0.32 | 704 | 26 |
| Total | - | - | 2654 | 100 |
| | | | | |
| Polyphenylene sulfide (PPS) | 1000 | 1.65 | 1650 | 87 |
| Sodium chloride | 1086 | 0.22 | 239 | 13 |
| Total | - | - | 1889 | 100 |
| | | | | |
| Polybuthylene terephthalate (PBT) | 1000 | 2.40 | 2400 | 93 |
| Methanol | 290 | 0.65 | 189 | 7 |
| Total | - | - | 2589 | 100 |

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## Data availability

All data that support the findings of study are included within the article