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Environmental and littering impacts of disposable cups made of polypropylene and polylactic acid in Germany

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ABSTRACT

As a result of improper management, plastics such as drinking cups are accumulating in environmental compartments worldwide, impacting biodiversity and ecosystem services. The goal of this study is to analyze and compare potential environmental impacts of disposable cups made of Polypropylene and Polylactic acid with the help of a cradle-to-grave life cycle assessment, including impacts related to the littering of these cups. Plastic pollution impacts are calculated based on the products' persistence in the environment, comparing the results of our own experiment to literature data. As an indication of the possible adverse health effects of Polypropylene and Polylactic acid, a toxicity test of the chemical mixtures migrating from the cups is conducted. Overall, the cups made of Polypropylene show lower environmental impacts compared to those made of Polylactic acid when the experimentally determined degradation rates are used. Nevertheless, regarding toxicity of the chemical migrates, the cup made of Polylactic acid performs better than the one made of Polypropylene. Considering all impact categories, there is no overall improvement in environmental impacts of producing the cup from Polylactic acid instead of Polypropylene. Our results indicate the importance of using degradation data measured specifically for the assessed product. Methodologically, we demonstrate a possible integration of life cycle assessment and safe-and-sustainable-by-design scoring. Further development of the plastic pollution impact category is needed to integrate effects on the terrestrial environment.

1. Introduction

Disposable drinking cups are widely used, e.g., at festivals or in stadiums, as a cheap and convenient way of consuming takeaway drinks. Around the world, many of the 500 billion disposable cups consumed each year are not disposed of properly (Lewis et al., 2021). This is also reflected in the fact that they are among the most common types of waste found on beaches around the world (Hanke, 2017). As a result of improper management, plastics are accumulating in environmental compartments worldwide (Li et al., 2016; Bergmann et al., 2019; Li et al., 2020), impacting biodiversity and ecosystem services (Steinmetz et al., 2016; Horton et al., 2017; Wong et al., 2020). Disposable drinking cups can be made of conventional plastic materials, e.g., Polypropylene (PP), or biobased and biodegradable materials such as Polylactic Acid (PLA). PLA is derived from renewable resources like corn or sugarcane and industrially compostable. Given the growing awareness of the environmental issues connected to the use of non-biodegradable materials, PLA is one of the most promising materials for commercially replacing conventional fossil-based materials like PP.

Life cycle assessment (LCA) is a common tool used to assess the possible environmental impacts of processes and products (ISO 14040:, 2009/Amd 1:2020; ISO 14044:, 2006/Amd 2:2020) and compare alternatives, such as producing a disposable cup from PP or PLA. There are existing assessments of products made of these materials, e.g., Vercalsteren et al. (2010), van der Harst and Potting (2013), Changwichan and Gheewala (2020), Cottafava et al. (2021), Lewis et al. (2021), and Moretti et al. (2021). However, all of these studies fail to address the impacts of littering and the toxicity of migrates from the cups. In fact, available impact assessment methodologies do not allow a full assessment of the impacts of plastic emissions (Sonnemann and Valdivia,

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2017; Woods et al., 2021; Maga et al., 2022). The goal of this study is, therefore, to analyze and compare the potential environmental impacts of disposable cups made of PP and PLA, including those impacts related to the littering of these cups, which is usually omitted in LCA studies. We thereby follow the example of Schwarz et al. (2024), who conducted a comparative LCA for two types of consumer multilayer packaging films and included macro- and microplastic emissions. We apply and extend the methodology previously suggested by Maga et al. (2022) to consider the impacts of plastic emissions in two ways: (i) by validating degradation rates obtained from the literature in an experiment and comparing the impact of the choice of degradation rate on the results and (ii) by integrating a toxicity assessment. We conduct in vitro toxicity tests of the chemical mixtures migrating from the cups and complement our findings with literature data. We then apply a scoring system to compare the potential impacts of toxicity, climate change, pollution, and resources as proposed by the Joint Research Center of the European Commission in the "Safe and Sustainable by Design" (SSbD) framework developed to assess chemicals and materials (Caldeira et al., 2023). We thereby combine an existing methodology with results obtained from degradation and toxicity experiments and apply them to different end-of-life scenarios involving littering. This provides a new and more comprehensive perspective on the environmental impacts of both types of disposable cups.

2. Materials and methods

2.1. Goal and scope

The goal of this study is to analyze the environmental impacts of two types of disposable cups made of either PP or PLA. According to the objective of the study, we define the functional unit as 1 transparent disposable plastic cup for cold drinks with a filling volume of 500 mL. The main characteristics of the disposable cups under investigation are given in Table 1.

The scope of the study covers all relevant life cycle stages from cradle-to-grave, including raw material extraction, the production of virgin granulate and cups, transport, the use stage (toxicity only), and end-of-life (EoL) treatment, including littering. The system boundaries are displayed in Fig. 1.

In the case of PP cups, granulate production includes crude oil extraction and transport, refining, and transport of granulates to the production facility of the cups. In the case of PLA, granulate production comprises the cultivation of biomass, including land use, the conversion of biomass (processing, fermentation, purification, logistics), and transport to the production facility. Cup production uses a thermoforming process in both cases. Packaging and distribution are excluded because they are the same for both investigated alternatives. Likewise, infrastructure such as extruders, forklifts, etc. are excluded. Two EoL scenarios per alternative are investigated to assess the sensitivity of the results to different waste treatments of the properly disposed cups: 1st 100 % thermal treatment in a municipal solid waste incineration plant with energy recovery and 2nd 100 % mechanical recycling into regranulates. The latter presupposes that the waste is collected separately in bins. The geographical scope is Germany and the data are representative for the year 2023.

Table 1
Characteristics of disposable cups made of PP and PLA.

Material	Polypropylene	Polylactic Acid
Weight	8.3423 g	11.3675 g
Volume	500 mL	
Wall thickness	150 µm	
Length	16 cm	
Top Diameter	9.0 cm	
Bottom Diameter	5.8 cm	

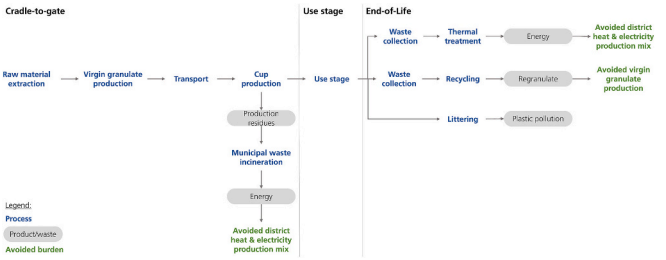

Fig. 1. System boundaries of the life cycle assessment of PP and PLA cups.

To assess the impacts of the littered plastic cups, characterization factors (CFs) are calculated according to the methodology suggested by Maga et al. (2022), applying a time horizon of 100 years. The degradation data are based on an experiment and are compared with literature data. When modeling the treatment of waste, the avoided-burden approach is applied. This means that credits are given for recovered energy or regranulate, as illustrated in Fig. 1. For the substitution of virgin polymers, we apply a quality correction-factor to take into account the quality of the recycled material compared to virgin material. As background data we use data sets from the Sphera® Managed LCA Content (MLC), which handle multifunctionality according to Sphera modeling principles (Sphera, 2024) and are consistent with the modeling choice of waste treatment in the foreground system.

2.2. Life cycle inventory of the disposable cups

The LCA scenarios are modeled using the software LCA for Experts by Sphera (version 10.7.1.28) and the latest Sphera Managed LCA Content (version 2024.21) database. Key assumptions regarding the life cycle inventory are summarized in Table 2. The detailed LCI can be found in Table 2 and Supplementary Information S1. As no primary data was available from the cup manufacturers, the LCA models are based on

Table 2
Life cycle inventory of plastic cup manufacturing, transport, usage, and end-of-life per FU.

Process	PP	PLA	Remarks
Polymer pellet production [in g]	8.42	11.51	Based on global production capacities (Moretti et al., 2021), we assume that 67 % of the PLA originates from NatureWorks (corn-based, USA) and 33 % from Total Corbian (sugarcane-based, Thailand).
Transport (freight train) [in km]	–	2000 (US) 200 (TH)	For PP, included in polymer pellet production
Transport (transoceanic ship) [in km]	–	6000 (US) 17,000 (TH)	Based on Moretti et al. (2021). For PP, included in polymer pellet production
Transport (truck) [in km]	200	300	Transport from within the country (PP) and the harbor (PLA) to the production site
Electricity demand extrusion & thermoforming [in kWh]	0.0138	0.215	Electricity consumption based on data provided by Moretti et al. (2021); German electricity grid mix
Residues extrusion & thermoforming [in %]	1	1	Typical losses due to start-up and shut-down
Stamping scrap re-entering extrusion & thermoforming [in %]	35	35	Similar to Maga et al. (2019a)
Plastic mass treated at the EoL [in g]	8.34	11.4	Incineration or recycling

US: United States of America, TH: Thailand.

secondary data, in particular data published by Moretti et al. (2021).

The cups are made of either PP or PLA. They differ mainly in weight owing to the different densities of the polymer types used. For the EoL, we assumed a littering rate of 2 % onto the soil (Jambeck et al., 2015). The plastic emission is assumed to have the shape of a formed film and a characteristic length (wall thickness) of 150 µm (see Table 1). The share of waste that is disposed of appropriately (98 %) is assumed to be incinerated as a base case, assuming that the cups are disposed of as municipal solid waste at the location of beverage consumption rather than being taken home to be adequately disposed of as lightweight packaging. Credits are awarded for electricity and district heat generated on the basis of the Germany electricity grid mix and the German district heat mix. To assess the sensitivity of the results to the EoL treatment, we also present results for an alternative waste treatment scenario: separate (homogenous) collection for mechanical recycling (e.g., at festivals or football stadiums). In this scenario, the mechanical recycling process of PP is modeled via foreground data taken from Franklin Associates (2018) (see Table S2 in Supplementary Information S1). The mechanical recycling of PLA is modeled on the basis of the scenario 2 data provided by Maga et al. (2019b). The recycling process includes shredding, airflow separation, washing, density separation, drying, electrostatic air flow separation, re-extrusion, and strand pelletizing (Maga et al., 2019b). In contrast to Maga et al. (2019b), we assume that the cups will be collected homogenously and are, therefore, transported without a sorting system.

To calculate the credits for the substitution of virgin material by recyclate, we apply two approaches: First, the value of the recyclate is determined on the basis of the economic value. In the case of PP, the substitution factor is calculated as 0.96 (0.81 €/kg recyclate according to plasticker (2024a) compared to 0.84 €/kg virgin PP according to plasticker (2024b)). For PLA, the substitution factor equals 0.42 (1.39 €/kg recyclate (plasticker (2024a)) compared to 3.30 €/kg virgin PLA (based on expert opinion). Second, the value of the recyclate is determined by its quality. Here, we use substitution factors of 0.9 for PP and 0.75 for PLA based on default values used in the Circular Footprint Formular and provided in annex C of the Environmental Footprint reference packages (European Commission, 2025). Although the European Commission does not specify default values for the quality of PLA recyclates, we have chosen the lower default value of 0.75 specified for LDPE films, as mechanical recycling of PLA is challenging owing to the decrease in molecular weight. In principle, PLA cups can also be industrially composted. Industrial composting, however, is the worst EoL alternative from an environmental point of view, as energy is required for industrial composting, CO_2 is emitted, and no valuable byproducts are produced from PLA (Rossi et al., 2015). This EoL option is, therefore, not analyzed further.

2.3. Characterization method of plastic impacts

To assess plastic pollution, we used the method of Maga et al. (2022). The method considers the redistribution of plastic emissions from the initial environmental compartment to other compartments via various natural mechanisms, such as wind or floatation/sinking, as well as degradation in the environment. The impacts of the redistribution of adjacent pollutants or leached additives to other compartments (van Cauwenberghe et al., 2013; Jambeck et al., 2015; Chae and An, 2018; Souza Machado et al., 2018; Wong et al., 2020) are neglected. The method does not differentiate the environmental risks of macro- vs. microplastics and, therefore, does not address fragmentation (breaking down of the emission into smaller pieces, ultimately generating micro- and nanoplastics). Instead, it focuses solely on the mass remaining in the environment. Regarding the differentiation of environmental compartments, we deviate from Maga et al. (2022) because they assume that emissions to soil are buried in the soil instead of laying on the soil surface. This assumption affects the redistribution and specific surface degradation rates (SSDRs). Since natural mechanisms transferring plastic emissions into deeper layers of soil are limited (Fauser et al., 1999; Hurley and Nizzetto, 2018), we assume that degradation rates measured inside soil do not apply to plastic emissions to the soil surface. Instead, we researched values for polymer degradation by sunlight and compared them to our own degradation experiment, which mimicked natural conditions at the surface of the terrestrial environment. As a result, we consider different studies than Maga et al. (2022) when extracting SSDRs for soil.

2.3.1. Accelerated weathering experiment

For the degradation experiments, commercial PP cups (AEP 600) and PLA cups (Bioware) were procured from Huhtamaki Foodservice Germany, GmbH & Co.KG, Bad Bertricher Str. 6–9, D-56859 Alf/Germany (Huhtamaki Foodservice Germany Sales GmbH & Co.KG, 2023). The commercially available PP cups differed from those modeled for the LCA in weight (6.3482 g instead of 8.3423 g) and height (14.5 cm instead of 16.0 cm). However, since the wall thickness is the same, we assume that the weight and height do not influence the degradation behavior. To better understand the underlying degradation mechanisms and effects, the cups were cryogenically ground via a Domel Tehtnica MillMix 20 ball mill (Domel, Zelezniki, Slovenia) and sieved to a particle size of $<$300 µm. Accelerated weathering of the PP and PLA grinds was performed at time intervals of 500 and 1000 h, respectively, and their surface morphology and chemical and thermal properties were compared. To deduce SSDRs, accelerated weathering of entire PP and PLA cups was performed at time intervals of 500, 1000, and 1544 h. Pristine PP and PLA are referred to as PP_{0h} and PLA_{0h}, respectively. The weathered PP and PLA samples are referred to as PP_{500h}, PP_{1000h}, PP_{1544h}, PLA_{500h}, PLA_{1000h}, and PLA_{1544h}, respectively.

Accelerated weathering was performed according to ISO standards 4892–2 (International Organization for Standardization, 2013) to simulate conditions found in nature. The samples were exposed to irradiation at 60 W/m^2 with a xenon lamp at 50 % relative humidity at a fan speed of 2000 rpm. The chamber temperature was maintained at 38 °C with a black standard temperature of 65 °C, as described in Budhiraja et al. (2022). For comparison, Sanary-sur-Mer, France, received an average UV solar radiation of 279 MJ/m^2 in 2021 (Atlas Material Testing Technology GmbH) and 2022 (Atlas Material Testing Technology GmbH), considering the wavelength range 295–385 nm. Taking day-night cycles into account, approximately 1292 h of degradation in a weathering chamber according to the ISO 4892-2 standard is equivalent to 1 year of degradation at Sanary, France. Based on the experiment duration and the amount of radiation applied, the maximum period of our weathering experiment (1544 h) is equivalent to 1 year, 2 months, and 11 days in Sanary, France. Details regarding the degradation experiment are given in Supplementary Information S2.

After the completion of the experiment, the samples were stored in the dark for further analysis. The chemical properties of the PP and PLA samples were evaluated via Fourier transform infrared spectroscopy (FTIR). The thermal properties were studied via differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA). The wettability and surface morphology were characterized via the contact angle (CA) and scanning electron microscopy (SEM), respectively. FTIR, DSC, TGA, and SEM were performed with ground PP and PLA particles, whereas the CA and SSDRs were evaluated with entire PP and PLA cups.

2.3.2. Degradation values from the literature

For degradation rates in compartments other than the soil surface, a literature review was conducted using the directory Web of Science and the keywords ‘degrad*’ in the abstract and ‘mass loss’, ‘oxygen demand’, ‘CO_2 generation’, and ‘CO_2 production’ in all fields in combination with ‘PP’, ‘polypropylene’, or ‘poly propylene’ as part of the abstract for PP and ‘PLA’, ‘poly lactic acid’, ‘polylactic acid’, or ‘polylactide’ for PLA. Applying the snowball principle, we also included relevant articles cited by those found during the initial literature review. The search yielded a total of 146 articles for PP and 337 for PLA. The articles were classified

based on their title and abstracts to identify relevant studies. Among the articles concerning PP, 49 % investigated the optimization of plastic products, 21 % described degradation studies under nonnatural conditions, 10 % researched plastic end-of-life treatment, and only 3 % contained relevant degradation data. Among the articles concerning PLA, 15 (5 %) were relevant for the study at hand. 61 % of the articles focused on the optimization of plastic products (e.g., for medical application, flame retardancy, etc.), 27 % described degradation studies under unnatural conditions, and 11 % were irrelevant for other reasons indicated in Table S7 in Supplementary Information S3. Based on the degradation data obtained from the literature review, SSDRs were calculated according to Maga et al. (2022), considering also studies measuring the loss of molecular weight, which were previously excluded by Maga et al. (2022). Meanwhile, we excluded degradation experiments conducted in compost as the corresponding conditions differ considerably from those found in nature.

2.3.3. Toxicity assessment

As an indication of the possible adverse health effects of PP and PLA products, we conducted an in vitro toxicity test of the chemical mixtures migrating from the cups. Migrates from the PP and PLA cups were obtained using ultrapure water and a water-ethanol mixture containing 10 % ethanol (EtOH) as simulants for aqueous foods according to European Regulation 10/2011/EU (Commission Regulation (EU), 2011). Two cups per treatment were filled with 500 mL of food simulant, closed with aluminum foil, and incubated at 40 °C for 10 days together with dishes containing ultrapure water to saturate the air and minimize evaporation from the food simulants. Two procedural blanks per solvent, consisting of a glass bottle closed with aluminum foil, were treated identically to control for contamination. Migrates were concentrated via solid-phase extraction and transferred to dimethylsulfoxide according to a previously published method (Zimmermann et al., 2021). CALUX reporter gene assays (BioDetection Systems B.V., Amsterdam) for human pregnane X receptor (PXR), peroxisome proliferator-activated receptor γ (PPARγ), estrogen receptor α (ERα), and androgen receptor (AR) were used to analyze the receptor activity of the extracts. The assays were performed as described in (Stevens et al., 2024b). The AR assay was conducted in antagonistic mode to detect the inhibition of the AR. Each extract was analyzed at five concentrations that were serially diluted 1:2, corresponding to 0.16-5 mg plastic per well.

To account for the variability of the chemical composition and, hence, the toxicity across different products, as well as to include a broader range of toxicity endpoints, we included data from the toxicity evidence map generated in the PlastChem report (Wagner et al., 2024, Annex A6). These data were filtered for studies that tested migrates of both PP and PLA cups, enabling a direct comparison within the same test system. Only one study by Zimmermann et al. (2021) met this criterion and was used to evaluate the toxicity of migrates of the PP and PLA cups (environmental and human toxicity).

2.4. Life cycle impact assessment methods

The environmental impacts were assessed via the life cycle impact assessment (LCIA) methods of the product environmental footprint (PEF) 3.1 recommended by the Joint Research Centre of the European Commission (European Commission, 2022), which were extended by a method accounting for plastic-related impacts. For the case study at hand, the CFs presented by Maga et al. (2022) for plastic pollution were updated by incorporating recent degradation studies, including an own degradation experiment (see subchapter 2.3). To indicate the sensitivity of the results to the degradation rates, we present the results for two scenarios: one using the measured SSDRs and one using SSDRs found in literature. To integrate the plastic pollution impact category with the PEF LCIA categories, the PEF-characterized midpoint indicator results were normalized via the normalization factors recommended by the EC-JRC (European Commission, 2022). The results of the plastic pollution impact category were normalized according to the factor suggested by Galafton et al. (2023) (150 kg PPe/(cap a)). For weighting, the factors suggested by the EC-JRC (Joint Research Centre of the European Commission, 2018) were combined with two weighting factors for plastic persistence (1.84 and 21.06 % according to Galafton et al. (2023)) by scaling down the weighting factors of the PEF impact categories to reach a total of 100 %.

To provide an additional perspective to the PEF and integrate the toxicity assessment of the chemical migrates, a scoring system was applied according to the suggestions for safe-and-sustainable-by-design (SSbD) chemicals and materials of the Joint Research Center of the European Commission (Caldeira et al., 2023). In this system, a so-called improved alternative (in our case, the PLA cup) is compared to a conventional alternative (here, the PP cup). Based on the numbers provided in section 3.3 “Life cycle impact assessment results”, the scores of each PEF impact category and two additional impact categories representing the toxicity assessment (ecotoxicity of chemical migrates and human toxicity of chemical migrates) were compared. For each category, a score was assigned to the improved alternative based on its outperformance over the conventional alternative. A score of 0 was assigned for a deterioration of up to 10 %, a score of 1 (no improvement) was assigned to a relative change of $-10 - +5$ % compared to the conventional alternative, a score of 2 (good improvement) was assigned for an improvement of 5–20 %, and a score of 3 (high improvement) was assigned to an improvement >20 %. The scores were calculated based on the impact scores provided in section 3.3 Life cycle impact assessment results. The impact categories were then aggregated into four groups based on their impact pathway (see Table 3): toxicity, climate change, resources, and pollution. For each of the four groups, the average of the impact scores was calculated. This means that all impact categories within a group were weighted equally. Finally, the average of the four groups was calculated to reach a single-score indicator. As a result, four different weighting factors were used for the impact categories of the different groups (25 % for climate change, 8 % for each impact category related to toxicity, 6 % for each impact category related to resources, and 3 % for each impact category related to pollution). In conclusion, this scoring system replaced the normalization and weighting steps of the PEF with a comparative scoring scale.

3. Results

3.1. Degradation rates of the cups

Due to its chemical structure, PP is prone to photodegradation and less sensitive to hydrolysis. As expected, PP presented the highest SSDR

Table 3
Groups and impact categories of the scoring system.

Group	Impact category
Climate change	Climate Change
Pollution	Acidification
	Eutrophication, freshwater
	Eutrophication, marine
	Eutrophication, terrestrial
	Ionizing radiation
	Ozone depletion
	Particulate matter
	Photochemical ozone formation
	Plastic pollution
Toxicity	Ecotoxicity, freshwater
	Ecotoxicity of chemical migrates
	Human toxicity, cancer
	Human toxicity, non-cancer
	Human toxicity of chemical migrates
Resources	Land Use
	Resource use, fossils
	Resource use, mineral and metals
	Water use

at the soil surface (7.0 μm/year), followed by marine water (2.5 μm/year) and then buried in soil (1.3 μm/year). From these values, we conclude that the PP cups did not contain an antioxidant stabilizer, which enabled a relatively quick degradation under the xenon lamp. PLA, on the other hand, is not very sensitive to mere UV degradation. In contrast, PLA, which contains ester bonds, is more susceptible to hydrolysis. For PLA, the highest SSDR is observed when buried in soil (57.0 μm/year), followed by the soil surface (0.9 μm/year). Degradation rates are minimal in water and sediments because PLA degrades at temperatures above 60 °C, which are not typically reached in freshwater or marine environments. In our experiments, weathered PP showed greater deterioration in characteristics than weathered PLA regarding changes in surface morphology, chemical properties, and thermal properties. After 1000 h of degradation, the PP cups were difficult to handle and any manual tempering led to their fragmentation. On the other hand, PLA did not show any fragmentation after the same interval of weathering. Details regarding the results of the degradation experiment can be found in Supplementary Information S2. The literature values regarding SSDRs for PP and PLA can be found in Supplementary Information S3.

Table 4 summarizes the degradation data found and deduced from our experiment and indicates the SSDRs used to calculate the CFs. It should be noted that the degradation rates reported in the literature for plastics buried in soil differ greatly from the rates we calculated for plastics on the soil surface based on our experimental data. Since we lack information regarding the precise composition of the materials, we can only assume that the PP cups do not contain an antioxidant stabilizer, facilitating a quick degradation. The influence of the degradation rates on the overall scores is shown in Fig. 4. According to the transfer coefficients suggested by Maga et al. (2022) for Germany, depending on their density, no PP emitted to soil ends up in river or marine sediment, and no PLA emitted to soil ends up in marine water. The displayed SSDRs result in a CF of 5.42 pt. for the flow “DE: PP film 0.15 mm (emission to soil)” and a CF of 44.47 pt. for the flow “DE: PLA film 0.15 mm (emission to soil)” using the measured SSDRs. For the scenario using SSDRs solely taken from the literature regarding degradation in soil (not on the surface), we calculated a CF of 27.79 pt. for the flow “DE: PP film 0.15 mm (emission to soil)” and 3.64 pt. for the flow “DE: PLA film 0.15 mm (emission to soil)”.

3.2. Toxicity assessment of the chemicals migrating from the cups

Only the PP water migrate activated the PXR receptor slightly (19 % of the reference compound) at the highest analyzed concentration (5 mg per well). None of the other receptors were activated by the chemical mixtures migrating from the cups (see Fig. 2). In the literature search for migration studies assessing the toxicity of PP and PLA cups, only one study by Zimmermann et al. (2021) was identified that tested both products, providing a direct comparison between the two. In this study, three in vitro assays related to human toxicity were performed. They comprised the assessment of oxidative stress via the AREc32 assay with the human breast cancer cell line MCF7 and yeast-based reporter gene assays with the human sex steroid receptors, the estrogen receptor alpha (ERα, YES), or the androgen receptor (AR, YAAS). Moreover, the baseline toxicity was investigated with the freshwater bacterium *Aliivibrio fisheri*. Compared to PLA, the PP migrates induced a more pronounced baseline toxicity, oxidative stress response, and antiangiogenic activity (Table S9 in Supplementary Information S4). Neither of the migrates induced estrogenic activity, which corresponds to the results of the present experiment. The cytotoxic effect of the PP migrates in the AREc32 and YAAS assays was also more pronounced than the effect induced by the chemicals migrating from the PLA cup. However, in the YES, the PLA migrates induced a stronger cytotoxicity than the PP migrates. To summarize, the chemicals migrating from the PP cups induced a more pronounced in vitro toxicity in both our experiment and the existing study.

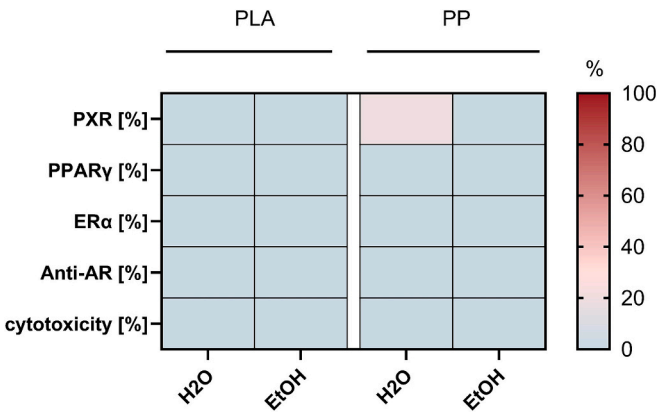

Fig. 2. Receptor activity of water (H_2O) and water-ethanol (10 %, EtOH) migrates from PLA and PP disposable cups at the highest tested concentration above the limit of detection, normalized to the reference compounds for the respective receptor.

3.3. Life cycle impact assessment results

Table 5 displays the impact scores of the compared scenarios. The lowest environmental impacts are marked in bold in Table 5 to highlight the most environmentally friendly scenarios. It can be observed that some of the PP scenarios with recycling and some of the PP scenarios with thermal treatment have the lowest environmental impact. The PLA scenario has higher scores in most impact categories by at least an order of magnitude compared to the respective PP scenario, except for the impact categories climate change and resource use (fossils). Especially the environmental impacts that are strongly linked to the cultivation of biomass such as eutrophication, particulate matter, land use, water use, acidification, and ecotoxicity show higher environmental impacts for the PLA cups.Fig. 3 shows the absolute impact scores of the compared scenarios: thermal treatment of PP cups, recycling of PP cups (substitution factors 0.96 and 0.9), thermal treatment of PLA cups, and recycling of PLA cups (substitution factors 0.42 and 0.75). The impact categories with the greatest contributions to the normalized and weighted total impacts are shown: climate change, freshwater ecotoxicity, resource use (fossil), and plastic pollution using the SSDRs based on the degradation experiments.

In the climate change impact category (Fig. 3a), the score of the PP scenario for thermal treatment is slightly higher than that of the PLA scenario, but lower for the recycling scenarios. In the case of the substitution factors based on the default values, the difference between the recycling scenarios becomes negligible. In the thermal treatment scenario of PP, the impacts on climate change are highly influenced by the EoL of the cups, including the incineration and recovery of energy (credits). The impacts of the recycling scenarios of PP are considerably lower because recycling at the EoL causes fewer greenhouse gas

Table 4
Specific surface degradation rates used to calculate characterization factors [in μm/year].

Environmental compartment	Terrestrial (buried)	Terrestrial (surface)	River sediment	Marine water	Marine sediment
PP	1.330 (0.884–4.671)	7.016	n.a.	2.537 (0.198–7.604)	n.a.
PLA	57.031 (0–186.224)	0.877	0.001	n.a.	0.001

Table 5
Impact scores of the compared scenarios.

Impact category	Unit	PP cups thermal	PP cups recycling (0.96)	PP cups recycling (0.9)	PLA cups thermal	PLA cups recycling (0.42)	PLA cups recycling (0.75)
Acidification	mol H^+ eq.	1.77E-05	**1.74E-05**	1.84E-05	1.87E-04	1.42E-04	9.78E-05
Climate change	kg CO_2 eq.	3.61E-02	**1.55E-02**	1.63E-02	3.23E-02	3.00E-02	2.11E-02
Ecotoxicity, freshwater	CTUe	2.67E-01	**1.00E-01**	1.14E-01	1.01E+00	6.55E-01	3.46E-01
Eutrophication, freshwater	kg P eq.	**1.13E-08**	5.60E-08	5.71E-08	1.42E-06	9.00E-07	4.57E-07
Eutrophication, marine	kg N eq.	**4.04E-06**	5.20E-06	5.47E-06	8.33E-05	5.92E-05	3.66E-05
Eutrophication, terrestrial	mol N eq.	**5.29E-05**	5.54E-05	5.83E-05	5.00E-04	3.97E-04	2.81E-04
Human toxicity, cancer	CTUh	6.52E-12	**3.58E-12**	3.89E-12	4.71E-11	3.03E-11	1.59E-11
Human toxicity, non-cancer	CTUh	2.32E-10	**8.92E-11**	1.02E-10	2.52E-10	1.98E-10	1.23E-10
Ionizing radiation	kBq U_{-235} eq.	**5.91E-04**	1.26E-03	1.27E-03	2.41E-03	2.43E-03	1.95E-03
Land use	pt	**-1.90E-02**	7.50E-02	7.60E-02	1.03E+00	7.06E-01	3.87E-01
Ozone depletion	kg CFC_{-11} eq.	**1.26E-13**	2.66E-13	2.69E-13	8.00E-10	4.77E-10	2.24E-10
Particulate matter	disease inc.	1.57E-10	**1.40E-10**	1.49E-10	2.22E-09	1.69E-09	1.20E-09
Photochemical ozone formation	kg NMVOC eq.	2.07E-05	**1.49E-05**	1.61E-05	1.18E-04	9.50E-05	6.78E-05
Resource use, fossils	MJ	5.20E-01	**2.32E-01**	2.60E-01	4.56E-01	4.07E-01	2.85E-01
Resource use, minerals & metals	kg Sb eq.	**1.50E-09**	1.92E-09	1.99E-09	2.13E-08	1.43E-08	7.86E-09
Water use	m^3 water eq. of deprived water	2.08E-03	**5.88E-04**	6.00E-04	1.68E-02	9.20E-03	4.52E-03
Plastic pollution	pt	**8.40E-04**	**8.40E-04**	**8.40E-04**	9.16E-03	9.16E-03	9.16E-03

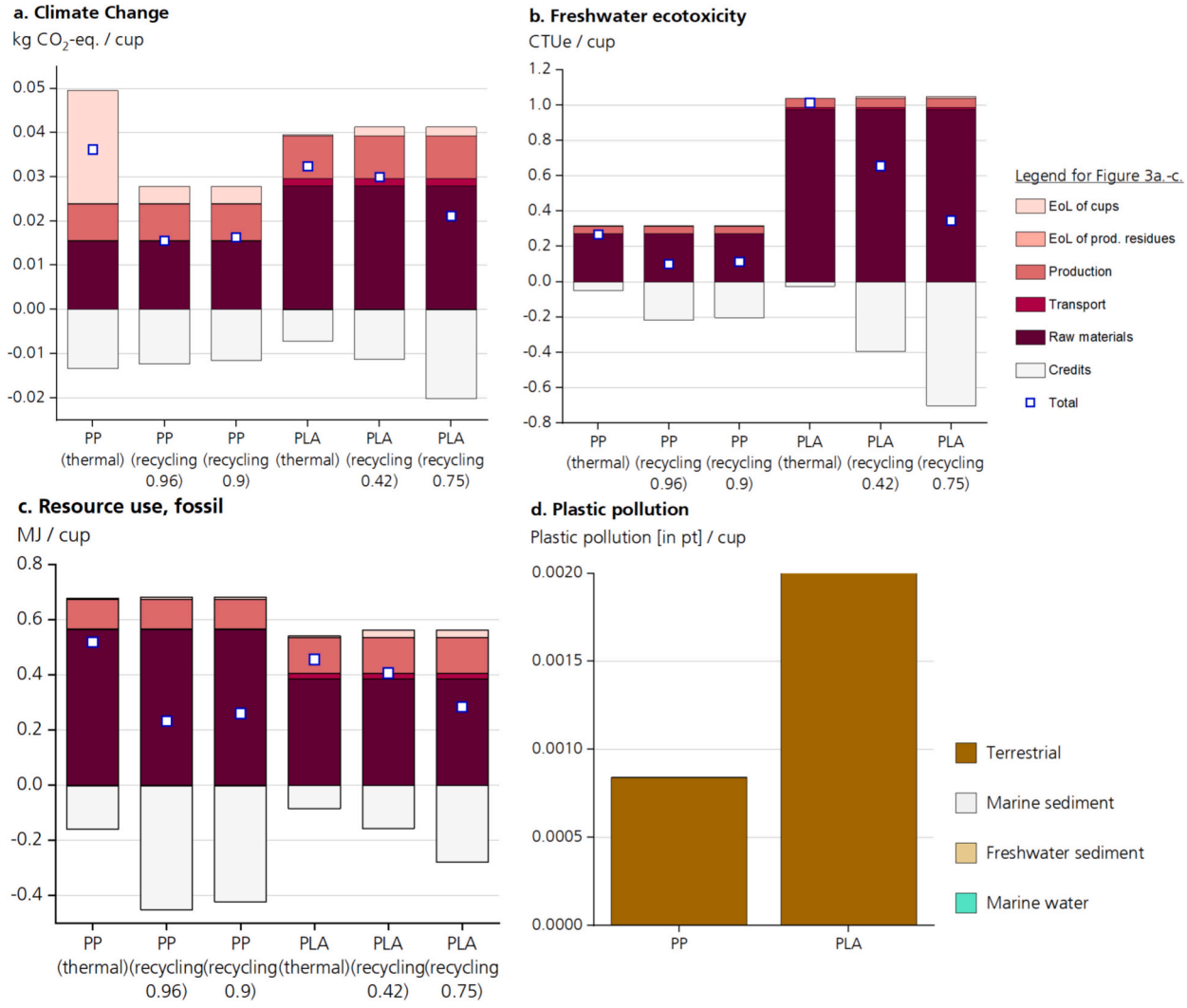

Fig. 3. Contribution of certain life cycle stages to the impact scores of the compared scenarios for the impact categories (a) climate change, (b) freshwater ecotoxicity, (c) resource use, fossils, and (d) plastic pollution using substitution factors for recyclates based on sales prices (0.96 for PP and 0.42 for PLA) and default values (0.9 and 0.75).

emissions than incineration does. However, the substitution of virgin PP results in lower credits than the substitution of energy gained from the incineration of the same amount of PP. For PLA, the climate change impacts of all scenarios are dominated by the raw material production, caused by the combustion of fossil resources during corn and sugarcane cultivation. Although the material itself is biobased, fossil fuels are required for its production. The credits for energy recovery in the thermal treatment of PLA are lower than those of PP due to the lower calorific value of PLA. Despite the higher quality of PP recyclates compared to PLA recyclates, which is expressed by the substitution factor for virgin material (0.96 or 0.9 for PP compared to 0.42 or 0.75 for PLA), the credits for PLA recyclate at the substitution factor of 0.75 is higher than that for PP. The contributions of transport and the EoL of production residues are rather small for all scenarios.

In all compared scenarios, the scores for freshwater toxicity (Fig. 3b) are largely determined by the raw material production. As a result, replacing virgin PP in the recycling scenario reduces the impacts by 68 or 64 % for PP (for a substitution factor of 0.96 or 0.9). The freshwater toxicity impacts of PLA cups are greater than those of PP cups in all scenarios. Here, too, the substitution of virgin PLA contributes to the reduction of toxicity impacts. For PLA, the freshwater toxicity impacts are mainly due to the use of pesticides during raw material production (application of Azodrin, Carbofuran, and Chlorpyriphos during sugar cane cultivation in Thailand and emissions of Acetochlor and Chloride during corn cultivation in the USA).

The scores for fossil resource use (Fig. 3c) are also largely driven by the raw material production for all compared scenarios. The production of PP granulate from crude oil consumes more fossil resources than the production of PLA granulate from corn or sugar cane. In the case of thermal treatment, this leads to a lower overall consumption of fossil raw materials for PLA cups. In the case of recycling, the PLA cup causes a higher consumption of fossil resources compared to the PP cup, as the credits for PLA recyclates are smaller due to the lower substitution factors.

Although the assumed littering rate is the same for both materials, the emitted plastic mass varies for the PP and PLA scenarios due to the different weights of the cups. Plastic emission equals 0.17 g/FU for the PP cups and 0.23 g/FU for the PLA cups. Based on the measured degradation rates, plastic pollution equals 0.84 g PPe/FU for the PP cups and 9.16 g PPe/FU for the PLA cups, independent of the EoL treatment option (see Fig. 3d). Because 97 % of plastic emissions to soil remain on soil in Germany and the degradation rate is higher on soil than in the other compartments for both materials, the vast majority of the plastic pollution impacts result from plastic pollution on soil. Using the degradation rates retrieved from the literature results in 4.43 g PPe/FU for the PP cups and 0.12 g PPe/FU for the PLA cups.

The normalized and weighted scores for all impact categories can be found in Supplementary Information S5. Fig. 4 displays the total impact scores of the compared scenarios after normalization and weighting. For better legibility, the impact categories are grouped into the same groups as those for the scoring: Climate change, toxicity, pollution (in this case, excluding plastic pollution), plastic pollution, and resources. In the graph on the left, the lower weighting factor for the impact category plastic pollution is used, and on the right, the higher weighting factor is used. The bars indicate the potential environmental impacts if the measured degradation rates are used for plastic pollution. The environmental impacts if using the SSDRs obtained from the literature are indicated by asterisks. As indicated in Fig. 4, the choice of degradation rate influences the total impact scores and even reverses the ranking of the two alternatives when using the higher weighting factor for plastic pollution.

PP cups have greater environmental impacts in the groups of climate change and resources, whereas pollution and toxicity have greater contributions in the case of the PLA cup. When using the lower weighting factor for plastic pollution, the biggest contributors to the PP scenarios are climate change (42.8–50.0 %) and resources (31.4–33.0 %). The plastic pollution category contributes 5.1–10.4 % to the overall impact of the PP cups. For the PLA scenarios, plastic pollution contributes the most, even with the low weighting factor (26.4–39.8 %), followed by climate change (20.8–22.8 %) and other impact categories grouped as “pollution” (18.2–22.7 %). When using the higher weighting factor, plastic pollution is the biggest contributor in all scenarios for both materials (38.1–57.1 % for PP and 80.4–88.3 % for PLA). Overall, the PP scenarios result in a lower total impact score than the PLA scenarios, regardless of the EoL treatment option and the weighting factor for plastic pollution when using the SSDRs based on our experiment with the assessed objects. When using the SSDRs obtained from the literature (indicated by an asterisk in Fig. 4), the total impact scores are much more similar for the two cup variants with the low weighting factor. With the higher weighting factor, the ranking of the cup variants is even reversed: for both EoL scenarios, the calculated potential environmental impacts of the PLA cups are lower than those of the PP cups.

3.4. Scoring of environmental impacts

For the thermal treatment EoL scenario, the impact scores of the PLA cups are higher than those of the PP cups in all impact categories except for climate change, fossil resource use, and the environmental and

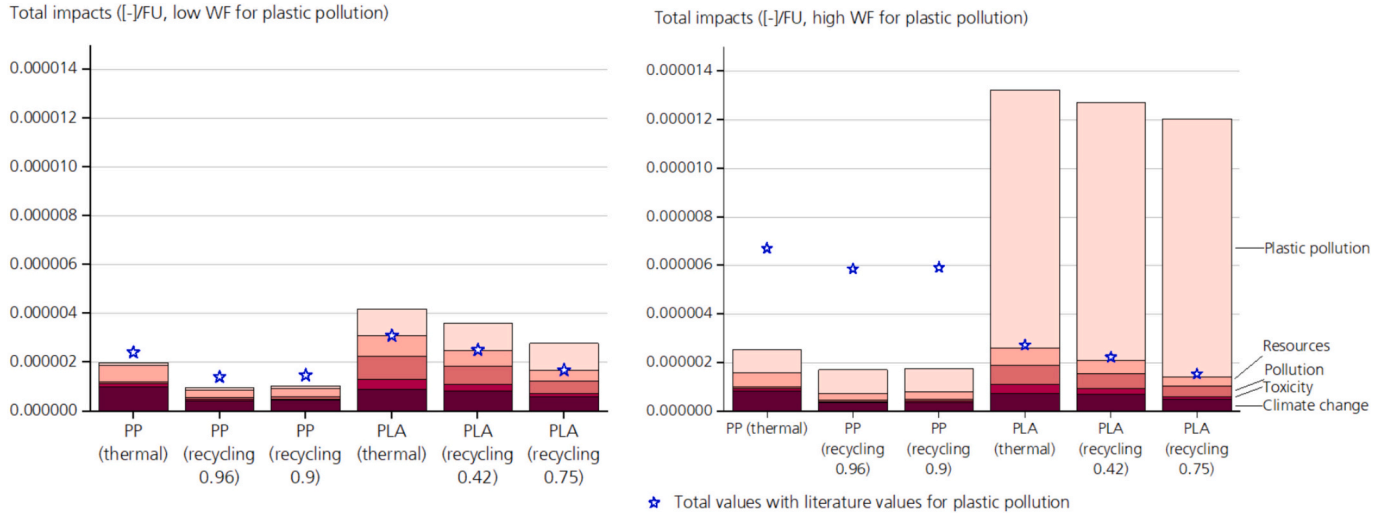

Fig. 4. Total impact scores of the compared scenarios after normalization and weighting.

human toxicity of the chemical migrates of the cups. Likewise, in the case of recycling for both pairs of substitution factors, the scores of the PLA scenario are higher in all impact categories, except, again, for the toxicity of the chemical migrates. That means, a "0" score is assigned to most impact categories comparing the "improved" PLA cups to the conventional PP cups. For the toxicity of the chemical migrates, in both environmental (baseline toxicity) and human toxicity (oxidative stress response and antiandrogenic activity) for both EoL scenarios and substitution factors, the PLA cup performs better (score 3) than the conventional PP cup. As a result, the total scores are 1.0 for the thermal treatment scenario, 0.3 for the recycling scenario with substitution factors based on sales prices, and 0.4 for the recycling scenario with substitution factors based on default values (see Table 6). That means that in all scenarios, there is no overall improvement of producing the cup from PLA instead of PP.

4. Discussion

The comparison of the LCIA results shows that in the thermal treatment scenario, the PLA cup has advantages over the PP cup in the impact categories of climate change and fossil resources consumption. However, if the cups are recycled at the EoL, the PP cups are more advantageous in these impact categories. This is due to the higher substitution factors for the PP recyclate, which lead to higher credits. From the point of view of plastic pollution, the PP cup performs better, as the PP cup degraded faster under the xenon lamp in the experiments than the PLA cup. In the fourth most important impact category after normalization and weighting, freshwater ecotoxicity, the PLA cup performs worse due to the use of pesticides in the production of corn and sugarcane. The total normalized and weighted scores also show advantages for the PP cup. Only when plastic pollution is given a high weighting factor and degradation rates from the literature are used, the PLA cup becomes more advantageous than the PP cup. If the toxicity analyses of the chemical migrates of the cups are included in the evaluation, this results in advantages for the PLA cup in the category "toxicity". Overall, the environmental impact of the PLA cup in the thermal treatment scenario remains similar to that of the PP cup (total score 1.0 in Table 6). In the case of recycling, the PLA cup performs worse overall (scores 0.3 and 0.4 in Table 6). While research groups focusing on plastic in the marine environment are able to compare impacts on an endpoint level (e.g., Corella-Puertas et al., 2023; Schwarz et al., 2024), there are currently no effect factors for the terrestrial environment. Consequently, we can only compare impacts on a midpoint level and apply normalization and weighting factors.

Plastic degradation in the environment is a complex process driven by multiple interacting factors. The first are the intrinsic properties, e.g., chemical structure, molecular weight, crystallinity, and presence of additives, fillers, or reinforcements. The second is the environment to which the material is exposed (environmental compartments such as soil, freshwater, marine water), and diverse environmental conditions such as UV exposure, temperature, relative humidity, and finally, the effects of pollutants such as heavy metals or persistent organic pollutants (POPs) adsorbing to the surface (Chamas et al., 2020; Sazali et al., 2020). The chemical structure of plastics determines their degradation mechanism. For example, PP with a carbon backbone undergoes oxidation and is resistant to hydrolysis, whereas PLA with its ester group is more sensitive to hydrolysis (Gorrasi and Pantani, 2018). As a result, the SSDR of PP is higher at the soil surface (7 μm/year) compared to the lower layers of soil (1.3 μm/year) due to its susceptibility to photodegradation. In contrast, PLA has a higher SSDR when buried in soil (57 μm/year) than at the surface (0.9 μm/year) because the soil provides better temperature and humidity conditions for its degradation. It is important to note that the weathering experiment focused solely on the photodegradation mechanism while excluding other mechanisms that naturally complement each other. Besides, our experiments neglected inhibiting factors such as shading by, e.g., plants. In the case of PP, this could lead to an overestimation of its degradation rate, as cups might be thrown in bushes or under trees where UV radiation is less abundant. In the case of PLA, isolating the photodegradation mechanism may have led to an underestimation of its degradation rate, as the environment in which the degradation experiment was conducted is not favorable for PLA and it did not reflect all contributing factors.

When considering the effects of weather on plastic, it is important to note that the solar radiation received by a geographical location can vary substantially. Weathering effects in different climate zones such as arid, subtropical, maritime with low or high solar radiation, and tropical can differ significantly. Notably, most plastics prone to photodegradation are sensitive to wavelengths between 300 and 350 nm. However, UV radiation, which ranges from 295 to 400 nm, makes up <10 % of total solar radiation (Pimentel Real, 2023). Calculating UV radiation intensity is complex due to the influence of dynamic climate factors. To estimate degradation in a weathering chamber relative to

Table 6
Scoring of the PLA cup compared to the PP cup (0 = deterioration (up to −10 %), 1 = no improvement (−10 − +5 %), 2 = good improvement (5–20 %), 3 = high improvement (>20 %)).

	Impact category	Thermal treatment			Recycling (substitution factors 0.96 and 0.42)			Recycling (substitution factors 0.9 and 0.75)		
		Rel. change	Score		Rel. change	Score		Rel. change	Score	
Climate change	Climate Change	11 %	2	2	−93 %	0	0	−30 %	0	0
Pollution	Acidification	−953 %	0	0	−717 %	0	0	−432 %	0	0
	Eutrophication, freshwater	−12,467 %	0		−1507 %	0		−700 %	0	
	Eutrophication, marine	−1961 %	0		−1040 %	0		−568 %	0	
	Eutrophication, terrestrial	−846 %	0		−616 %	0		−381 %	0	
	Ionizing radiation	−308 %	0		−94 %	0		−54 %	0	
	Ozone depletion	−636,941 %	0		−179,530 %	0		−83,194 %	0	
	Particulate matter	−1317 %	0		−1103 %	0		−704 %	0	
	Photochemical ozone formation	−470 %	0		−538 %	0		−321 %	0	
	Plastic pollution	−991 %	0		−991 %	0		−991 %	0	
Toxicity	Ecotoxicity, freshwater	−279 %	0	1.4	−554 %	0	1.2	−204 %	0	1.2
	Ecotoxicity of the chemical migrates	478 %	3		478 %	3		478 %	3	
	Human toxicity, cancer	−623 %	0		−748 %	0		−309 %	0	
	Human toxicity, non-cancer	−8 %	1		−122 %	0		−20 %	0	
	Human toxicity of the chemical migrates	1103 %	3		1103 %	3		1103 %	3	
Resources	Land Use	−5536 %	0	0.5	−841 %	0	0	−409 %	0	0.3
	Resource use, fossils	12 %	2		−75 %	0		−9 %	1	
	Resource use, mineral and metals	−1316 %	0		−643 %	0		−296 %	0	
	Water use	−705 %	0		−1465 %	0		−653 %	0	
Total				1.0			0.3			0.4

real-world conditions, calculations were based on UV radiation in the 295–385 nm range from Sanary-sur-Mer, France (see chapter "methods" and Supplementary Information S2).

Of the tested PP and PLA cups, only the chemicals migrating from the PP cup activated the PXR receptor, while the other receptors were not activated. Based on these results, the PP cup releases more chemicals inducing in vitro toxicity. However, the generalizability of these results for PP and PLA cups is limited as the toxicity results are specific to the tested products. Plastic food contact articles are chemically diverse; many different compounds with the same functionality are available, and non-intentionally added substances further increase the chemical diversity (Wiesinger et al., 2021). This chemical diversity can result in differences in in vitro toxicity induced by chemical mixtures released from plastic food contact articles. Toxicity can be highly variable between products, even if made of the same polymer and comprising the same function (Stevens et al., 2024a & 2024b, Zimmermann et al., 2019, 2021). To account for this diversity and include a broader range of toxicity endpoints, we included migrate toxicity studies from a literature search to evaluate the toxicity of PP and PLA cups. Only one study compared the toxicity migrating from a PP and PLA cup (Zimmermann et al., 2021). In this study, the PP cup migrate elicited more in vitro toxicity than the PLA cup, which is in line with our findings. Luminescence inhibition of the freshwater bacterium *Aliivibrio fischeri* is indicative of baseline toxicity and is commonly used to evaluate the toxicity of aquatic environments (Escher et al., 2018). In the tests involving human-based endpoints, chemicals migrating from both types of cups induced general modes of toxicity, such as oxidative stress response and PXR activation, as well as more specific modes of action (antiandrogenic activity). However, the PP cup migrates induced stronger effects overall.

4.1. Comparison to existing literature

Previous studies, e.g., the meta-analysis published by the Life Cycle Initiative of the United Nations Environment Programme (Lewis et al., 2021) concluded that disposable cups have a similar environmental impact regardless of the material they are made of, such as biobased plastic, fossil-based plastic, or paper. They also concluded that reusable cups for cold drinks, e.g., those made of stainless steel or polycarbonate, are the better choice from an environmental point of view. Several other studies confirm the first conclusion, e.g., Franklin Associates (2006), Changwichan and Gheewala (2020), Cottafava et al. (2021), and Moretti et al. (2021). Vercalsteren et al. (2010) also investigated the environmental impacts of disposable cups made of PP and PLA. The results show trade-offs and do not allow a clear conclusion for the selection of the most environmentally favorable cup system. As in the meta-study by van der Harst and Potting (2013), the weight of the cup played an important role in determining the impacts in our study. Due to the different material properties and densities of the polymers, the PLA cup has a higher mass than the PP cup.

Our impact scores are comparable to those previously published, although most of them focus on climate change impacts and very few on other impact categories. For example, Franklin Associates (2006) calculated a similar climate change impact as our global warming impact results for cups with a volume of 473 mL (16 oz) but a slightly higher weight (10.5 and 14.8 g compared to 8.3 and 11.4 g in our study). Likewise, Moretti et al. (2021) came to a similar climate change impact (14.5 and 17.5 g CO_2-eq./ PP and PLA cup, respectively) for cups with a volume of 200 mL and a significantly lower weight (3.9 and 4.6 g). If the impact scores of previous studies are normalized to the weight of the cups in this study, as shown in Table 7 for the impact categories global warming and resource use fossil, the results and are mostly comparable depending on the chosen EoL scenario. None of the previous studies assessed freshwater ecotoxicity or investigated plastic emissions or persistence related to the littering of the cups.

4.2. Limitations of the LCA study and experiments

One limitation of the LCA study is that the cup producer did not provide primary data for their production processes. However, reliable data on the production of disposable cups made of PP and PLA could be found in the literature. Another aspect is the design of the disposable cups, which is influenced by the different material properties. In this LCA study, the same cup design was assumed for simplicity's sake. However, differences in the density of the materials were taken into account. In general, the resilience of the applied LCIA methods used varies. In particular, the toxicity impact categories and the input-based impact categories such as fossil resource consumption or water impact are associated with higher uncertainties (Joint Research Centre of the European Commission, 2018). A further limitation is that the results are representative for Germany and cannot be transferred to other geographic areas. This applies in particular to the degradation behavior in the environment, which is highly dependent on climatic conditions.

Further uncertainties exist with regard to the measurability of plastic degradation. Weathering is a complex phenomenon involving the interaction of heat, light, oxygen, air, water, mechanical stress, and biotic interactions. The photodegradation chemistry of PP and PLA in a weathering chamber differs from that in the environment. These discrepancies can be attributed to factors such as the light source, the ingress of oxygen during the light/dark cycle, the absence of mechanical stress, fluctuating temperature, and interactions with moisture. Following ISO standards for weathering experiments need not mimic the various environmental matrices and conditions, but it aids in standardization, facilitates comparison with data from previous studies, and allows for future research.

We conducted our analysis not for the materials PP and PLA in general, but for a specific product (disposable cups) with specific characteristics. Most importantly, the PP cups seemed not to contain antioxidant stabilizer, which enabled a relatively quick degradation under the xenon lamp. This may be because as a single-use item, the cup does not require stabilizers. Consequently, our results are not necessarily transferable to other products made of PP and PLA, which may contain other additives. This holds true also regarding toxicity. Furthermore, the endpoints included in the toxicity analysis, the interference with four nuclear receptors of the endocrine and metabolic system, does not reveal a complete picture. By including data from literature in the assessment, we aimed for an expansion to additional products and endpoints. However, only one suitable study was identified. Concluding, there is a need for more research regarding the toxicity of leachates from specific products, comparing different alternatives by applying the same experimental setup and spanning a wider range of endpoints.

As already mentioned, the calculated plastic pollution equivalents only consider the persistence of plastics in the environment; neither

Table 7
Comparison of our impact scores to existing literature values normalized to the weight of our investigated alternatives.

Impact category		Franklin Associates (2006)	Changwichan and Gheewala (2020)	Cottafava et al. (2021)	Moretti et al. (2021)	Our study
Climate change [g CO2-eq.]	PP	27.4	6.7–12.8	16.7–22.6	31.0	15.5–36.2
	PLA	39.2	5.7–6.8	16.0–33.4	43.2	21.1–32.4
Resource use (fossils) [MJ]	PP	n.r.	0.17	n.r.	0.64	0.23–0.6
	PLA	n.r.	0.12	n.r.	0.44	0.28–0.46

n.r. = not reported.

exposure nor effects on organisms are taken into account. However, the toxicity tests carried out indicate that migrates from the PLA cup have a lower toxicity compared to migrates from the PP cup.

5. Conclusions

In summary, based on our assumptions for this particular case, it can be said that the disposable cup made of PP performs better from an environmental point of view than the variant made of PLA. We arrive at this interpretation both by normalization and weighting of the results and by using the scoring system proposed by the SSbD framework. This also applies when considering the potential environmental impact of plastic emissions, especially as the PP cup degraded faster than the PLA cup in the experiments under the xenon lamp. The sensitivity analysis regarding the quality factor used for the substitution of virgin material showed that high-quality mechanical recycling of PLA can improve the environmental performance of PLA cups. However, depending on the weighting factor applied for plastic pollution, the total impact scores of PP cups are still considerably lower than those of PLA cups, even with a substitution factor of 0.75 for PLA. The PLA cup only outperforms the PP cup when using a high weighting factor for plastic pollution and literature data for the degradation rate of PP and PLA on soil. Regarding human and ecotoxicity of the chemicals migrating from the cups, toxicity tests indicate advantages of the PLA cup over the PP cup.

The impact categories climate change, freshwater ecotoxicity, fossil resource use, and plastic pollution were identified as most significant by means of normalization and weighting. The considerable influence of plastic pollution on the environmental impact score shows that it is important to carry out degradation experiments with the particular material or product to be assessed. For example, the assumed absence of UV stabilizers in the tested cups made of PP leads to comparatively high degradation rates. If, on the other hand, the cups were buried in (industrial) compost, the PLA cup would tend to degrade faster. This highlights that the precise material composition, as well as the fate and environmental conditions are decisive for the degradation rate of plastics in the environment.

Further development of the plastic pollution impact category with regard to exposure and effect factors for the terrestrial environment would be desirable. At present, such factors have only been developed for the sea and not for soils. However, as the majority of plastic emissions occur on soil, further methodological development is particularly important for this environmental compartment.

In addition to plastic pollution, toxicity of the chemical migrates of products is often neglected in LCAs. One of the main reasons for this is the large number of potentially toxic substances that are often unknown and, therefore, cannot be assessed using the recommended USEtox method. Moreover, toxicity data regarding the chemicals migrating from products into foods are largely missing. The study showed that a toxicity assessment, as required by the SSbD framework, can improve the assessment of variants and should, therefore, be carried out if within the constraints and available budgets.

CRediT authorship contribution statement

Christina Galafton: Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Vaibhav Budhiraja:** Writing – original draft, Visualization, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Writing – review & editing. **Sarah Stevens:** Writing – original draft, Visualization, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Branka Mušič:** Resources, Formal analysis. **Daniel Maga:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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Declaration of competing interest

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2025.04.013.

Data availability

All relevant data is included in the article and supplementary information.

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