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CHALLENGES OF COMPARATIVE LIFE CYCLE IMPACT ASSESSMENT AND TERRESTRIAL ECO-TOXICITY MEASUREMENT. A CASE STUDY OF FOSSIL-BASED PET VERSUS ITS RECYCLED AND BIO-BASED COUNTERPARTS

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Purpose: The primary goal of this research is to compare the results of the LCIA phase based on the 2008 and 2016 versions of the ReCiPe method at the midpoint level and to identify interpretation problems related to the measurement of **terrestrial ecotoxicity**. The aspiration, however, is to support the scientifically and technically sound development of LCIA methods that provide reliable and reproducible results.
Design/methodology/approach: Life cycle assessment (LCA) was applied to compare the environmental performance of fossil-based PET plastic and its two increasingly used alternatives, i.e. recycled PET (rPET) and bio-based polylactic acid (PLA). Data for modelling was retrieved from the ecoinvent database (3.6), SimaPro (release 9.1). The results of LCIA are presented at the midpoint level with both ReCiPe2008 and ReCiPe2016, with a hierarchist (H) perspective.
Findings: Although the research showed some differences in the LCIA results performed with ReCiPe 2008 and ReCiPe2016, there is a general convergence of results, except for the terrestrial ecotoxicity. Thus, rPET has the best environmental profile across the range of impact categories analysed, with few exceptions (human toxicity: cancer and non-cancer, freshwater ecotoxicity and marine ecotoxicity), regardless of the version of the ReCiPe method. The use of ReCiPe2016 leads to significant differences in the results of terrestrial ecotoxicity compared to the use of ReCiPe2008. The contribution analysis at the level of inventory results shows that there is a discrepancy in substances contributing to a given terrestrial ecotoxicity score.
Originality/value: The variation in results using ReCiPe2008 and its updated version ReCiPe2016 does not substantially change the conclusions obtained, except for the terrestrial ecotoxicity category. For practitioners, this means that further research and clarification on the modelling of terrestrial ecotoxicity is necessary as to achieve the best available practice.

Keywords: circular economy, life cycle impact assessment (LCIA), polyethylene terephthalate (PET), polylactic acid (PLA), recycled plastics.

Category of the paper: Research paper, Technical paper.

1. Introduction

Life cycle impact assessment (LCIA) constitutes the third phase of life cycle assessment (LCA). Its aim is to understand and evaluate the magnitude and significance of potential environmental impacts of a product throughout its life cycle (ISO, 2006a). Consequently, LCIA involves a complex sequence of steps through which the man-made interventions in the form of an inventory data are further processed and sorted into classes according to either the effect they have on the environment (impact categories) or the damage they cause to the environment (areas of protection) (Rybaczewska-Błażejowska, 2019). Given the great complexity of the LCIA phase, an average LCA practitioner has limited knowledge of the dependencies between inventory data and impact categories/areas of protection, characterisation models and category indicators, and thus applies standard LCIA methods, such as ReCiPe, ILCD2011 or CML-IE for the calculation.

The international standards ISO 14040 and ISO 14044, regulating the LCA methodology, do not recommend one specific method for the performance of the LCIA phase. They, however, define a series of recommendations concerning the selection of impact categories, category indicators and characterisation models including, inter alia: 1) the impact categories shall represent the aggregated impacts of life cycle inventory (LCI), 2) value-choices and assumptions made during the selection of impact categories should be minimised, 3) the characterisation models needs to be scientifically and technically valid, 4) the extent to which the characterisation model and the characterisation factors are scientifically and technically valid should be identified, and finally 5) the category indicators are to be environmentally relevant (ISO, 2006b). Naturally, the LCIA phase shall be strongly coordinated with the remaining LCA phases to reduce possible omissions and sources of uncertainty.

Although there is a spectrum of methods supporting the performance of the LCIA phase, the practice shows that ReCiPe is one of the most often used LCIA methods worldwide. The ReCiPe method was first developed in 2008 through cooperation between RIVM and Radboud University, CML and PRé Consultants (Huijbregts et al., 2016; Rybaczewska-Błażejowska, Sulerz, 2017). Subsequently, it was updated in 2016 to make harmonised category indicators at two levels: eighteen midpoint impact categories and three areas of protection at three different perspectives: the individualistic, the hierarchist and the egalitarian.

Despite the fact that both ReCiPe2008 and ReCiPe2016 versions cover eighteen impact categories at the midpoint level and three areas of protection at the endpoint level, there is no direct translation between impact categories. Consequently, ReCiPe2016 encompasses the following impact categories: global warming (GWP) (kg CO_2 eq), stratospheric ozone depletion (ODP) (kg CFC-11 eq), ionising radiation (IRP) (kBq Co-60 eq), fine particulate matter formation (PMFP) (kg PM2.5 eq), photochemical oxidant formation: ecosystem quality

(EOFP) (kg NOx eq), photochemical oxidant formation: human health (HOFP) (kg NOx eq), terrestrial acidification (TAP) (kg SO2 eq), freshwater eutrophication (FEP) (kg P eq), marine eutrophication (MEP) (kg N eq), human toxicity: cancer (HTPc) (kg 1,4-DCB), human toxicity: non-cancer (HTPnc) (kg 1,4-DCB), terrestrial ecotoxicity (TETP) (kg 1,4-DCB), freshwater ecotoxicity (FETP) (kg 1,4-DCB), marine ecotoxicity (METP) (kg 1,4-DCB), land use (m^2a crop eq) (LOP), water use (WCP) (m3), mineral resource scarcity (SOP) (kg Cu eq), fossil resource scarcity (FFP) (kg oil eq). The endpoint level is related to the following areas of protection: human health (HH) (DALYs), ecosystem quality (ED) (species*year) and resource scarcity (RA) ($) (Huijbregts et al., 2016). The approaches at the midpoint and endpoint levels are complementary, but there is a stronger relation to the environmental flows and thus lower uncertainty at the midpoint level (Hauschild, Huijbregts, 2015).

The goal of this research is to systematically compare the results of the LCIA phase based on the 2008 and 2016 versions of the ReCiPe method at the midpoint level and to identify interpretation problems related to the measurement of terrestrial ecotoxicity. For this, a case study of fossil-based PET plastic and its two increasingly used alternatives, i.e. recycled PET (rPET) and bio-based polylactic acid (PLA) are used (Rybaczewska-Błażejowska, Mena-Nieto, 2020). The aspiration of this research is to support the scientifically and technically sound development of LCIA methods that provide reliable and reproducible results.

2. Methods

The research is fully compliant with the international standards ISO 14040 and ISO 14044 and thus consists of four phases: the goal and scope definition, inventory analysis, impact assessment and interpretation (ISO, 2006a; ISO, 2006b). It is partially based on the former author's study regarding "Comparative life cycle assessment of fossil polyethylene terephthalate (PET) and its recycled and bio-based counterparts" (Rybaczewska-Błażejowska, Mena-Nieto, 2020), but taking into consideration many modifications resulting from the application of updated SimaPro version (release 9.1) and ecoinvent database. In addition, current research follows an attributional approach and presents the LCIA results using both ReCiPe2008 and ReCiPe2016.

2.1. Goal and scope definition

The scope of LCA covers conventional fossil-based PET plastic and its two supposed sustainable alternatives, i.e. 100% recycled PET (rPET) and bio-based plastic, i.e. polylactic acid (PLA). The functional unit is 1 metric tonne of plastic. For all plastics, the system boundary covers the manufacturing stage (cradle-to-gate analysis), but obviously, the plastics are made of different raw materials: petroleum, post-consumer PET or corn starch.

2.2. Inventory analysis

Data for modelling of the plastics manufacturing was retrieved from the ecoinvent database (3.6) (Ecoinvent Centre, 2019). Consequently, the inventory data regarding the PET manufacturing process are based on the average unit process from the eco-profiles of the European plastic industry. The inventory data for the rPET manufacturing process is based on the PET recycling data for Europe and includes all processes of the production of recycled PET granulate, amorphous. Finally, the inventory data for the PLA manufacturing process is based on the data from the world's largest bio-plastics producer, i.e. Nature-Works LLC, and thus has a global context. However, regarding PLA the market process was applied and thus inputs from transport processes are included, since it has replaced the process of PLA production, which was available in the former version of the ecoinvent database.

2.3. Impact assessment

Calculations of the environmental profiles of PET, rPET and PLA were done with the use of ReCiPe2008 (Goedkoop et al., 2013) and ReCiPe2016 (Huijbregts et al., 2016), hierarchist (H) perspective. The results are presented at the midpoint level. However, taking into account the requirement of the ISO 14044 regarding the LCA comparative assertions that the category indicator can only be compared with exactly similar category indicator, the research encompasses the following impact categories: global warming (GWP), terrestrial acidification (TAP), freshwater eutrophication (FEP), marine eutrophication (MEP), human toxicity: cancer and non-cancer (HTPc and HTPnc), **terrestrial ecotoxicity** (**TETP**), freshwater ecotoxicity (FETP), marine ecotoxicity (METP), water use (WCP) and fossil resource scarcity (FFP).

3. Results and discussion

The results of the research are twofold. The first relates to the comparative analysis of the manufacturing processes of fossil-based PET plastic, rPET and PLA. Taking into account the argumentations of Bueno et al. (2016) that the former versions of a given method could draw to different conclusions, the result are discussed based on ReCiPe2016. The second relates to the comparative analysis of the results of the LCIA phase of the aforementioned plastics, especially regarding terrestrial ecotoxicity, using ReCiPe2008 and ReCiPe2016.

The research proved that rPET has the best environmental profile in almost all examined impact categories, regardless of the version of the ReCiPe method (Figure 1). And thus, rPET has the lowest characterisation values in the following impact categories: global warming – 1140 kg CO2 eq, terrestrial acidification – 2.81 kg SO2 eq, freshwater eutrophication – 0.514 kg P eq, terrestrial ecotoxicity – 5430 kg 1,4-DCB, water use – 10.6 m3 and fossil

resource scarcity – 285 kg oil eq of ReCiPe2016. Concurrently, the fossil-based PET plastic has very promising characterisation results in the following impact categories: marine eutrophication – 0.0823 kg N eq, human toxicity: cancer and non-cancer – 2637.2 1,4-DCB, freshwater ecotoxicity – 154 1,4-DCB and marine ecotoxicity – 200 1,4-DCB. PLA demonstrates the worst characterisation results in comparison to fossil-based PET plastic according to ReCiPe2016, except for the categories of fossil resource scarcity – 830 kg oil eq and surprisingly terrestrial ecotoxicity – 9490 kg 1,4-DCB. The greatest difference occurs in the category of marine eutrophication where the characterisation value for PLA is equal to 1.3 kg N eq.

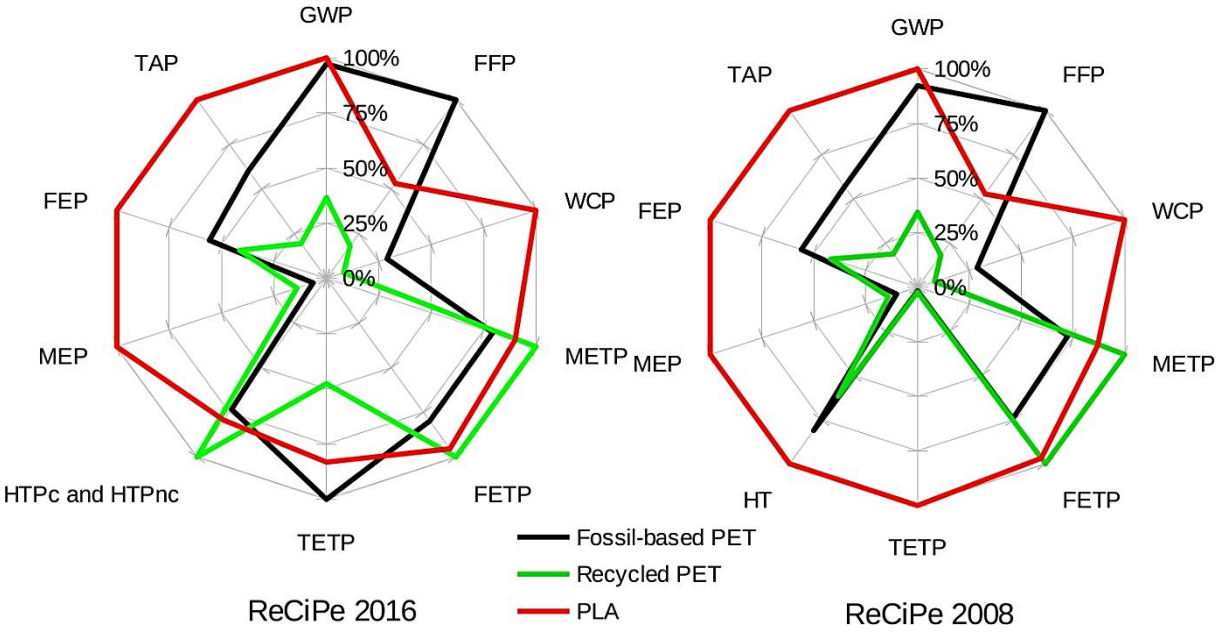

Figure 1. Characterisation results for fossil-based PET plastic, rPET and PLA using ReCiPe2016 and ReCiPe2008.

There are some differences in the LCIA results using ReCiPe2008 and ReCiPe2016, though to varying extent (Figure 2). In practice, this means that there are – either impact categories, such as for instance marine eutrophication, having considerably better characterisation results using ReCiPe2016 (0.502; 0.7; 5.0 kg N eq in ReCiPe2008 versus 0.0823; 0.182; 1.3 kg N eq in ReCiPe2016 for fossil-based PET plastic, rPET and PLA respectively) – or impact categories, such as for instance human toxicity: cancer and non-cancer (HTPc and HTPnc), having much worse characterisation results using ReCiPe2016 (764; 582; 942 kg 1,4-DB eq in ReCiPe2008 versus 2637.2; 3600.5; 2857.8 kg 1,4-DB eq in ReCiPe2016 for fossil-based PET plastic, rPET and PLA respectively). However, there are also impact categories having almost similar characterisation profiles in ReCiPe2008 and ReCiPe2016. These are freshwater eutrophication, water use and fossil resource scarcity. Just to illustrate this point, the characterisation results for the last case are as follows: 1590; 290; 840 kg oil eq in ReCiPe2008 versus 1560; 285; 830 kg oil eq in ReCiPe2016 for fossil-based PET plastic, rPET and PLA respectively.

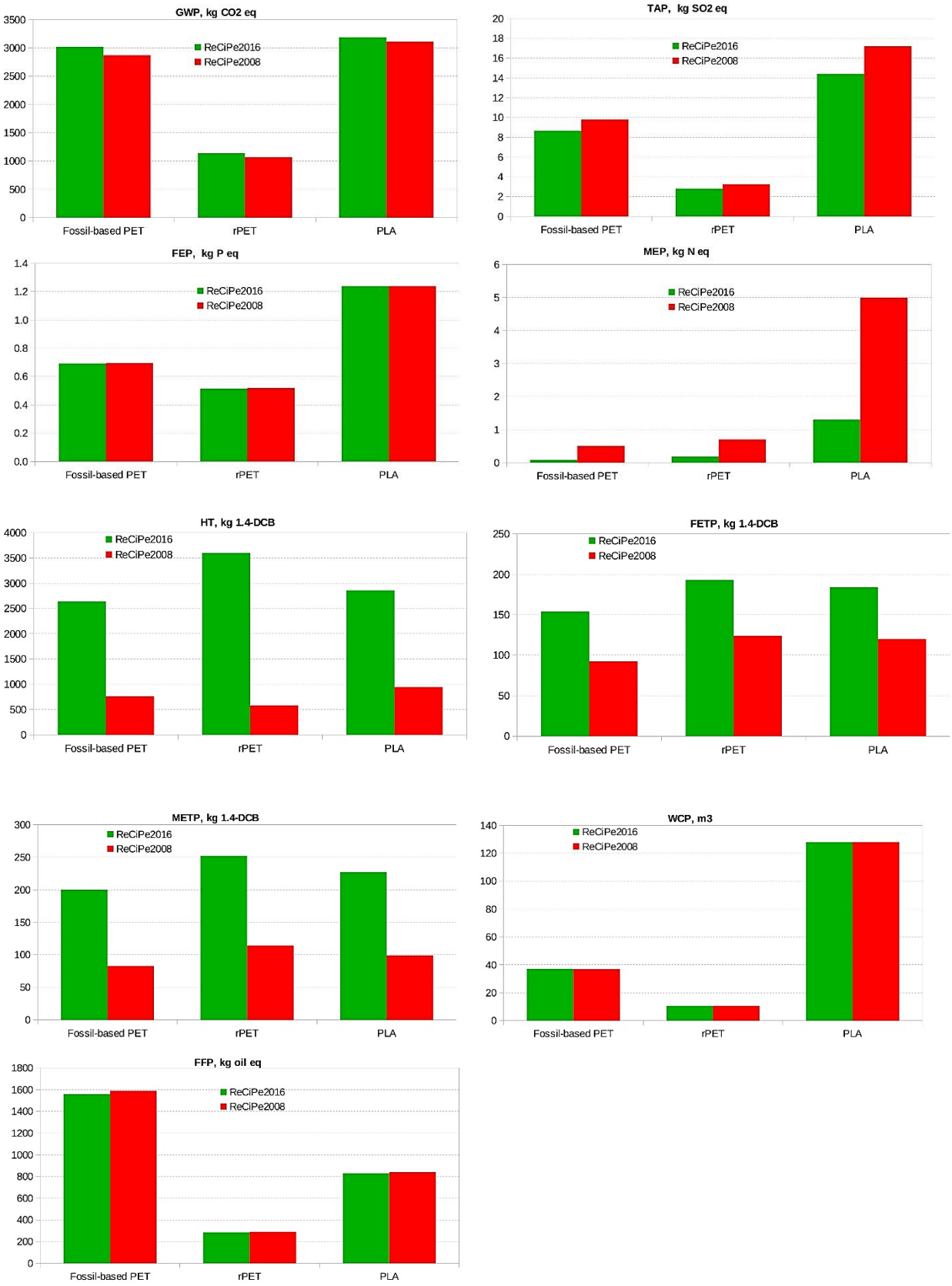

Figure 2. A comparison of characterisation results (without terrestrial ecotoxicity) for fossil-based PET plastic, rPET and PLA using ReCiPe2016 and ReCiPe2008.

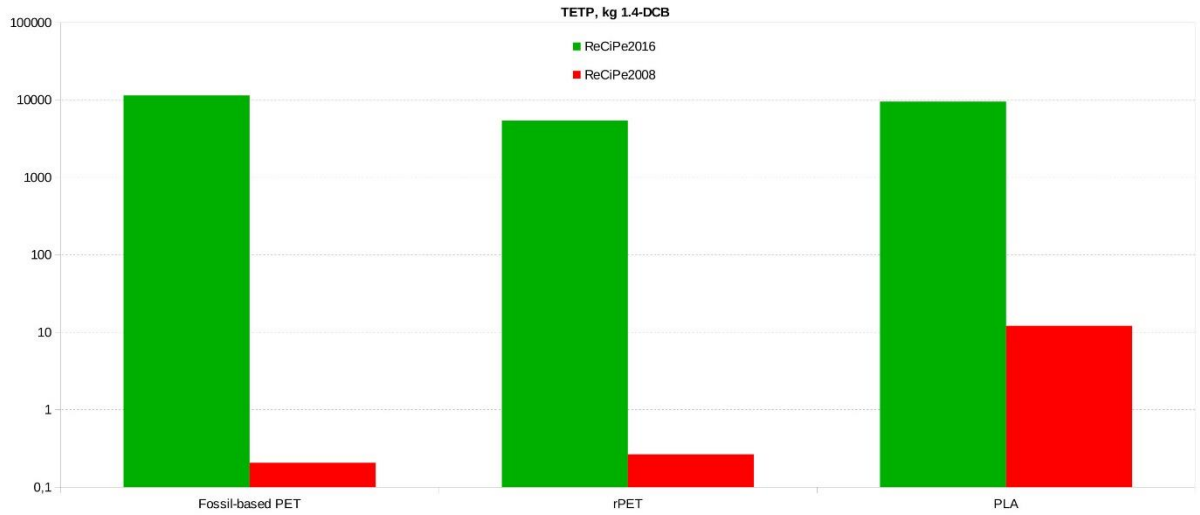

Figure 3. Characterisation results for terrestrial ecotoxicity for fossil-based PET plastic, rPET and PLA using ReCiPe2016 and ReCiPe2008 [in logarithmic scale].

Although the use of ReCiPe2016 leads to different characterisation results compared to the use of ReCiPe2008, the interpretation of the results does not change significantly except for the impact category of terrestrial ecotoxicity. Figure 3 shows in logarithmic scale the difference in the absolute values of terrestrial ecotoxicity when the calculations were done with ReCiPe2008 and ReCiPe2016. And thus, the characterisation results for terrestrial ecotoxicity are equal to 0.206; 0.266; 12.1 kg 1,4-DB eq in ReCiPe2008 versus 11400; 5430; 9490 kg 1,4-DB in ReCiPe2016 for fossil-based PET plastic, rPET and PLA respectively. In addition, an increase in the level of terrestrial ecotoxicity is uneven, since it falls within the range of 784 for PLA – 55339 for PET. In consequence, the comparative analysis of the manufacturing process of fossil-based PET plastic, rPET and PLA using ReCiPe2008 and ReCiPe2016 leads to different conclusions. ReCiPe2008 gives priority to fossil-based PET, followed by rPET, whereas ReCiPe2016 to rPET followed by PLA.

The toxicity set of categories encompasses human toxicity, freshwater, marine and land ecotoxicity in both ReCiPe2008 and ReCiPe2016 (Acero et al., 2015). Consequently, terrestrial ecotoxicity is one of the impact categories within the above set and thus it is subject to the same methodological rules. The characterisation factor for toxicity accounts for the environmental persistence (fate), accumulation in the human food chain (exposure), and toxicity (effect) of a chemical. Comparing with ReCiPe2008 the following updates in the toxicity calculation were introduced: separate midpoint factors for human cancer and non-cancer effects, fate and exposure for dissociating organics were included, the USEtox organic and inorganic database was implemented (incl. 3073 organic chemicals and 20 metals), the individualistic perspective of 20 years time horizon was added, linear effect factors were included, effects on agricultural soil were excluded (Huijbregts et al., 2016). Terrestrial ecotoxicity itself expresses hazard-weighted increase in natural soils and its unit is kg 1,4-dichlorobenzene-equivalents (1,4-DCB) to industrial soil. Details regarding the modelling of terrestrial ecotoxicity, including characterisation models, are somehow limited and thus, in reality, the interpretation of results poses certain difficulties.

Contribution analysis identified substances having the greatest contribution to the results of terrestrial ecotoxicity for individual types of analysed plastics using ReCiPe2008 and ReCiPe2016. Table 1 and Table 2 shows that regarding fossil-based PET plastic – copper, nickel, zinc, antimony and vanadium – have substantial contribution to the results of terrestrial ecotoxicity regardless of the version of the ReCiPe method. The contribution of individual metals is, however, different and thus, for instance, copper constitutes 35.05% in ReCiPe2008 versus 64% in ReCiPe2016. There is similar situation regarding rPET, where – copper, antimony, zinc, vanadium, nickel and silver – have the greatest contribution to the results of terrestrial ecotoxicity, but their percentage share is different depending on the version of the ReCiPe method. And thus, for instance the contribution of copper to the results of terrestrial ecotoxicity equals 38% in ReCiPe2008 versus 65% in ReCiPe2016. Concerning PLA, apart from copper, entirely different substances are associated with the impact category of terrestrial ecotoxicity using ReCiPe2008 and ReCiPe2016. These are predominantly atrazine metolachlor, azoxystrobin, cypermethrin and terbuthylazin in ReCiPe2008 versus copper, nickel, antimony, vanadium and zinc in ReCiPe2016. Additionally, the contribution of copper to the results of terrestrial ecotoxicity equals less than 1% (0.56%) in ReCiPe2008 versus 67% in ReCiPe2016. Finally, it is worth emphasizing that notwithstanding the type of analysed plastic and the version of the ReCiPe method, 10 identified substances contributes to 89% – 99% of the results of terrestrial ecotoxicity.

Table 1.
Contribution analysis for terrestrial ecotoxicity for fossil-based PET plastic, rPET and PLA using ReCiPe2016

	Fossil-based PET	Amount [in %]	rPET	Amount [in %]	PLA	Amount [in %]
1.	**Copper**	64.12	**Copper**	64.83	**Copper**	67.33
2.	**Nickel**	16.67	**Antimony**	14.51	Nickel	7.09
3.	**Zinc**	4.64	**Zinc**	4.57	Antimony	6.99
4.	**Antimony**	4.07	**Vanadium**	4.25	Vanadium	5.10
5.	Chromium	3.25	**Nickel**	3.35	Zinc	5.06
6.	**Vanadium**	2.44	Chromium	2.39	Lead	1.91
7.	Lead	1.72	**Silver**	1.34	Chromium	1.78
8.	Arsenic	0.89	Mercury	1.28	Mercury	1.16
9.	Cadmium	0.88	Lead	1.11	Arsenic	0.92
10.	Mercury	0.69	Arsenic	0.45	Cadmium	0.90
Total		**99.36**		**98.09**		**98.23**

Table 2.
Contribution analysis for terrestrial ecotoxicity for fossil-based PET plastic, rPET and PLA using ReCiPe2008

	Fossil-based PET	Amount [in %]	rPET	Amount [in %]	PLA	Amount [in %]
1.	**Copper**	35.05	**Copper**	37.97	Atrazine	55.70
2.	**Nickel**	20.20	**Zinc**	14.29	Metolachlor	29.26
3.	Bromine	10.15	Cypermethrin	9.89	Azoxystrobin	4.27
4.	Acetic Acid	5.44	Bromine	6.65	Cypermethrin	2.20

Cont. table 2.

5.	**Vanadium**	4.34	Metam-sodiumdihydrate	4.51	Terbuthylazin	1.89
6.	**Zinc**	3.98	**Antimony**	3.52	Terbufos	1.49
7.	Cypermethrin	3.09	**Vanadium**	5.73	Alpha-cypermethrin	0.93
8.	**Antimony**	2.57	**Silver**	2.65	Isoxaflutole	0.69
9.	Copper	2.15	**Nickel**	2.29	Chlorpyrifos	0.61
10.	Selenium	2.05	**Zinc**	2.04	**Copper**	0.56
Total		**89.00**		**89.53**		**97.60**

4. Conclusions

The research shows that rPET has lower environmental impacts than the corresponding fossil-based PET and PLA across the range of impact categories analysed, with few exceptions. These are human toxicity: cancer and non-cancer (HTPc and HTPnc), freshwater ecotoxicity and marine ecotoxicity (METP) following the ReCiPe2016 method. Concurrently, given the present state of the art, PLA does not demonstrate sufficiently superior environmental performance compared to conventional fossil-based PET, which should be a condition of market entry in a circular economy.

The presented research confirms that the results of the LCIA phase are based on relative measures and thus are largely dependent on both the method that is selected and the version of the same method. This is exactly the case regarding ReCiPe and thus the use of ReCiPe2016 leads to different characterisation results compared to the use of ReCiPe2008 in absolute value. The variation in results, however, does not substantially change the conclusions obtained, except for the terrestrial ecotoxicity category. Considering the aforementioned arguments, the author posits that the LCIA method (incl. the version of the same method) should be clearly defined in any LCA research, including the reasons for its selection.

Calculations done with the use of ReCiPe2016 for the category of terrestrial ecotoxicity give the priority to rPET followed by PLA and fossil-based PET plastic, whereas ReCiPe2008 gives the priority to fossil-based PET plastic, followed by rPET and PLA. This all makes that giving an unequivocal recommendation for the optimal material from the point of view of the terrestrial ecotoxicity for packaging manufacturers is very difficult. And these are actually the expectations of decision-makers creating a circular economy for plastic materials. Consequently, it is strongly recommended to investigate the usefulness and the feasibility of the methodological approaches for the modelling of terrestrial ecotoxicity as to achieve the best available practice.

Although the research allows a number of interesting conclusions to be drawn, there are still issues that require deeper evaluation. The reasons for the discrepancy in results between ReCiPe2008 and ReCiPe2016 are one of them. Consequently, the forthcoming research should encompass different products, the endpoint areas of protection and other perspectives (individualistic and egalitarian). This would definitely provide deeper insight into the methodology of the ReCiPe method, including the value choices and modelling steps.

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