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Supplementary Information for:

Modeling marine microplastic emissions in Life Cycle Assessment: Characterization factors for biodegradable polymers and their application in a textile case study

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Content

Supplementary note 1: Fate factors and GLAM characterization factors of the studied polymers

Table S1: Fate factors in seawater and sediment compartments of PCL, PLA, and PBSA.

Polymer	Shape	Size (µm)	Fate in water (d)	Fate in sediments (d)
PCL	Sphere	5000	5.78E+01	1.12E+04
		1000	2.66E+01	2.84E+03
		100	1.64E+01	2.89E+02
		10	1.06E+01	2.01E+01
		1	2.58E+00	4.91E-01
	Fiber	5000	6.72E+01	1.38E+04
		1000	2.98E+01	3.71E+03
		100	1.69E+01	3.89E+02
		10	1.17E+01	2.93E+01
		1	3.27E+00	8.29E-01
	Film	5000	8.21E+01	1.77E+04
		1000	3.59E+01	5.34E+03
		100	1.79E+01	5.88E+02
		10	1.29E+01	4.85E+01
		1	4.46E+00	1.69E+00
PLA	Sphere	5000	1.51E+02	3.63E+04
		1000	1.03E+02	2.33E+04
		100	3.33E+01	4.63E+03
		10	1.75E+01	5.00E+02
		1	1.25E+01	3.98E+01
	Fiber	5000	1.56E+02	3.77E+04
		1000	1.14E+02	2.63E+04
		100	3.82E+01	5.95E+03
		10	1.82E+01	6.68E+02
		1	1.33E+01	5.64E+01
	Film	5000	1.61E+02	3.91E+04
		1000	1.28E+02	3.01E+04
		100	4.71E+01	8.35E+03
		10	1.96E+01	1.00E+03
		1	1.43E+01	9.01E+01
PBSA	Sphere	5000	1.31E+02	3.09E+04
		1000	7.14E+01	1.49E+04
		100	2.40E+01	2.17E+03
		10	1.58E+01	2.14E+02
		1	9.53E+00	1.35E+01
	Fiber	5000	1.39E+02	3.31E+04
		1000	8.21E+01	1.78E+04
		100	2.66E+01	2.84E+03
		10	1.64E+01	2.89E+02
		1	1.06E+01	2.01E+01

	Film	5000	1.49E+02	3.57E+04
		1000	9.79E+01	2.20E+04
		100	3.14E+01	4.13E+03
		10	1.72E+01	4.40E+02
		1	1.21E+01	3.41E+01

Table S2: GLAM characterization factors (CFs) for PCL, PLA, and PBSA.

Polymer	Shape	Size (μm)	GLAM midpoint CF (PAF*year/ $kg_{emitted}$)	GLAM endpoint CF (PDF*year/ $kg_{emitted}$)
PCL	Sphere	5000	5.01E+07	6.25E-11
		1000	1.34E+07	1.67E-11
		100	1.38E+06	1.73E-12
		10	9.55E+04	1.19E-13
		1	3.24E+03	4.04E-15
	Fiber	5000	6.09E+07	7.59E-11
		1000	1.73E+07	2.16E-11
		100	1.87E+06	2.33E-12
		10	1.39E+05	1.73E-13
		1	5.08E+03	6.32E-15
	Film	5000	7.80E+07	9.71E-11
		1000	2.46E+07	3.07E-11
		100	2.83E+06	3.52E-12
		10	2.29E+05	2.85E-13
		1	9.50E+03	1.18E-14
PLA	Sphere	5000	1.84E+08	2.29E-10
		1000	1.25E+08	1.55E-10
		100	2.87E+07	3.58E-11
		10	3.29E+06	4.10E-12
		1	2.79E+05	3.48E-13
	Fiber	5000	1.90E+08	2.37E-10
		1000	1.38E+08	1.72E-10
		100	3.64E+07	4.53E-11
		10	4.38E+06	5.46E-12
		1	3.89E+05	4.85E-13
	Film	5000	1.97E+08	2.45E-10
		1000	1.56E+08	1.94E-10
		100	4.98E+07	6.20E-11
		10	6.53E+06	8.13E-12
		1	6.13E+05	7.63E-13
PBSA	Sphere	5000	1.56E+08	1.95E-10
		1000	8.10E+07	1.01E-10
		100	1.31E+07	1.63E-11

	10	1.34E+06	1.67E-12
	1	9.44E+04	1.18E-13
	5000	1.66E+08	2.07E-10
	1000	9.50E+07	1.18E-10
Fiber	100	1.71E+07	2.13E-11
	10	1.81E+06	2.25E-12
	1	1.37E+05	1.70E-13
	5000	1.78E+08	2.22E-10
	1000	1.15E+08	1.43E-10
Film	100	2.45E+07	3.05E-11
	10	2.73E+06	3.40E-12
	1	2.25E+05	2.81E-13

Supplementary note 2: Conversion of characterization factors to ReCiPe methodology

The characterization factors were primarily developed for the IMPACT World+ methodology (Corella-Puertas et al. 2023). Therefore, they had to be converted to be applicable to the endpoint category unit of damage on ecosystem quality. This was achieved by using the average species density in marine ecosystems of 3.46E-12 species/m^3 (as proposed for the ReCiPe methodology (Huijbregts et al. 2017)) and the average continental seawater depth of 100 m, according to the USEtox model (Fantke et al. 2017)).

Supplementary note 3: Life cycle inventory modeling of the case study

The sports shirt production was assumed to occur in China, one of the largest textile producing countries worldwide. It starts with the yarn production, for which PLA granulate is used. The yarn is knitted and dyed, with textile waste going to incineration without energy recovery (as assumed by Horn et al. (2023)). The knitted fabric is cut and assembled into a shirt. The packaged shirt is shipped to the Netherlands where it is used for 52 times. After each use the shirt is washed and occasionally dried (34% of the washing cycles (Sandin et al. 2019)). For the end-of-life, a simplified model was built, taking into account a mixed fate according to latest data on textile waste in the Netherlands. These include the incineration with energy recovery in the Netherlands (55%) and the export to countries such as Pakistan which serves as an example here (European Environmental Agency 2023).

Modeling details are provided in the following tables:

- **Production phase:** Table S3 - Table S7
- **Transport phase:** Table S8
- **Use phase:** Table S9 - Table S11
- **End-of-life phase**: Table S12 - Table S15

Table S3: Life cycle inventory of the yarn production in China, considering the functional unit as described in the manuscript.

Activity	Quantity	Unit	Notes
Input			
PLA granulate	0.201	kg	Ecoinvent 3.9 dataset for PLA
Fiber spinning	0.201	kg	See Table S4
Yarn spinning	0.199	kg	See Table S5
Output			
PLA yarn to knitting	0.198	kg	
PLA waste	-	kg	Included in spinning and yarning

Table S4: Life cycle inventory of the PLA fiber spinning, considering 1 kg of fiber., based on (Sandin et al. 2019) model of melt spinning of polyester.

Activity	Quantity	Unit	Notes
Input			
Lubricating oil	0.01	kg	
Antimony	0.0002	kg	
Toluene diisocyanate	0.0002	kg	
Electricity	1.5	kWh	
Heat	2.2	MJ	
Output			
PLA waste	0.01	kg	To incineration

Table S5: Life cycle inventory of the yarn production, based on Sandin et al. 2019, assuming the worst case of yarning PES; per 1 kg of spun yarn

Activity	Quantity	Unit	Notes
Input			
Electricity	3.8	kWh	
Lubricant	0.0016	kg	
Output			
PLA waste	0.005	kg	To incineration

Table S6: Life cycle inventory of the knitting and dyeing for one shirt. According to private communication and ecoinvent 3.9.

Activity	Quantity	Unit	Notes
Input			
Electricity	0.072	kWh	
Oil	0.003	kg	
Dyeing of knitted fabric	0.188	kg	Based on Sandin et al. 2019, adapted to Chinese energy mix
Output			
PLA waste	0.005	kg	To incineration

Table S7: Life cycle inventory for garment preparation and assembly of one shirt, based on Moazzem et al. (2018) and Horn et al. (2023).

Activity	Quantity	Unit	Notes
Input			
Electricity	0.448	kWh	
Polyester thread	0.0006	kg	
Heat	0.012	MJ	
Water	0.030	L	
Wicking chemical	0.002	kg	
Plastic packaging	0.002	kg	
Paper hangtags	0.002	kg	
Output			
Wastewater to treatment	0.030	L	
PLA waste fabric	0.005	kg	To incineration

Table S8: Life cycle inventory for transport within China and shipping from China to the Netherlands.

Activity	Quantity	Unit	Notes
Transport within China by truck			
Truck	0.201	tkm	Assuming a generic distance of 1000 km
Shipping to the Netherlands			
Sea freight transport to Rotterdam	2.961	tkm	Based on sea-distances.org
Transport from Rotterdam to Appeldoorn	0.021	tkm	Exemplary transport distance within NL

Table S9: Life cycle inventory of the use phase of the functional unit.

Activity	Quantity	Unit	Notes
Online order delivery			Based on Hischier 2018
Transport – lorry	0.026	tkm	Adapted to NL
Transport - van	0.007	tkm	Adapted to NL
Laundry			
Washing	8.32	kg	52 washing cycles according to functional unit; see Table S10
Drying	2.91	kg	35% of washing cycles; see Table S11

Table S10: Life cycle inventory of the washing process, based on Sandin et al. 2019, scaled on 1 kg of laundry.

Activity	Quantity	Unit	Notes
Input			
Water	6.2	L	
Detergent	0.016	kg	Average detergent
Electricity	0.225	kWh	
Output			
Wastewater to treatment	5.2	L	

Table S11: Life cycle inventory of the tumble-drying process, based on Sandin et al. 2019, scaled on 1 kg of laundry.

Activity	Quantity	Unit	Notes
Input			
Electricity	0.67	kWh	
Output			
Wastewater to treatment	1	L	

Table S12: Life cycle inventory of the PLA textile waste treatment in municipal incineration in the Netherlands, assuming a share of 55% of total waste and allocating 100% of burdens and benefits of the incineration to the shirt's life cycle (i.e., allocation factor of 1).

Activity	Quantity	Unit	Notes
Input			
Transport for collection	0.009	tkm	Generic transport for collection by truck
Shirt incineration	0.088	kg	Assuming polyester incineration in municipal incineration plant
Output			
Electricity from incineration of PLA, avoided impact	0.093	kWh	Electricity efficiency: 0.21; heating value: 18.2 MJ/kg
Heat from incineration of PLA, avoided impact	0.320	MJ	Heat efficiency: 0.20

Table S13: Life cycle inventory of the PLA textile waste exported to Pakistan (serving as an exemplifying case); assuming 0.045 open burning, 0.2655 landfilling, and 0.1395 recycling (allocation factor of 0.5)

Activity	Quantity	Unit	Notes
Incineration (open burning)			
Transport to Pakistan	0.007	kg	See Table S14
Open burning of the shirt	0.007	kg	
Landfilling (open dump)			
Transport to Pakistan	0.042	kg	See Table S14
Landfilling of the shirt	0.042	kg	
Recycling			
Transport to Pakistan	0.011	kg	See Table S14
Mechanical recycling of textile	0.011	kg	See Table S15

Table S14: Life cycle inventory for transport from the Netherlands to Pakistan, per 1 kg of textile.

Activity	Quantity	Unit	Notes
Truck transport within NL	0.1	tkm	Assuming a generic transport distance of 100 km
Sea freight transport from NL to South Asian Pakistan Terminals	11.358	tkm	According to routescanner.com

Table S15: Life cycle inventory for mechanical recycling of waste textile, based on Duhoux et al. (2021), per 1 kg of textile.

Activity	Quantity	Unit	Notes
Input			
Electricity	0.5	kWh	
Water	0.02	kg	
Output			
Spinnable fibers	0.25	kg	
Fluff	0.075	kg	Substituting polyester fiber
Filling material	0.3	kg	Substituting polyurethane foam

Supplementary note 3.1: Calculations of the microplastic inventory

We used the Plastic Footprint Network's recommendations (Plastic Footprint Network 2024) to calculate the plastic emissions of the FU per life cycle stage. Additionally, a worst-case scenario ("high emissions" scenario) was implemented that assumes the emission of the textile waste that is not incinerated in NL. For the worst case, a fragmentation rate of 100% was used, i.e., the macroplastics would fragment completely into microplastics. The emissions per life cycle stage are shown in Table S16.

Table S16: Plastic emissions associated with the FU of one sports shirt throughout its entire life cycle based on the PLP for granulate emissions and PFN for microfiber emissions.

Life cycle stage	Occurrence of emission	Formation	Release Rate Ocean	Amount (mg) per kg	Amount (mg) per jersey
Yarn production	CN	Granulate	1.00	1.00E-05	2.01E-06
Knitting and dyeing	CN	Microfiber	0.97	2.38E+02	4.7E+01
Laundry	NL	Microfiber	0.07	2.54E+02	4.07E+01
End-of-life	PK	Microfiber	1.00		6.26E+04
Total base case					8.76E+01
Total worst case					6.27E+04

Supplementary note 4: Example of a microscopic image and cell count graphs

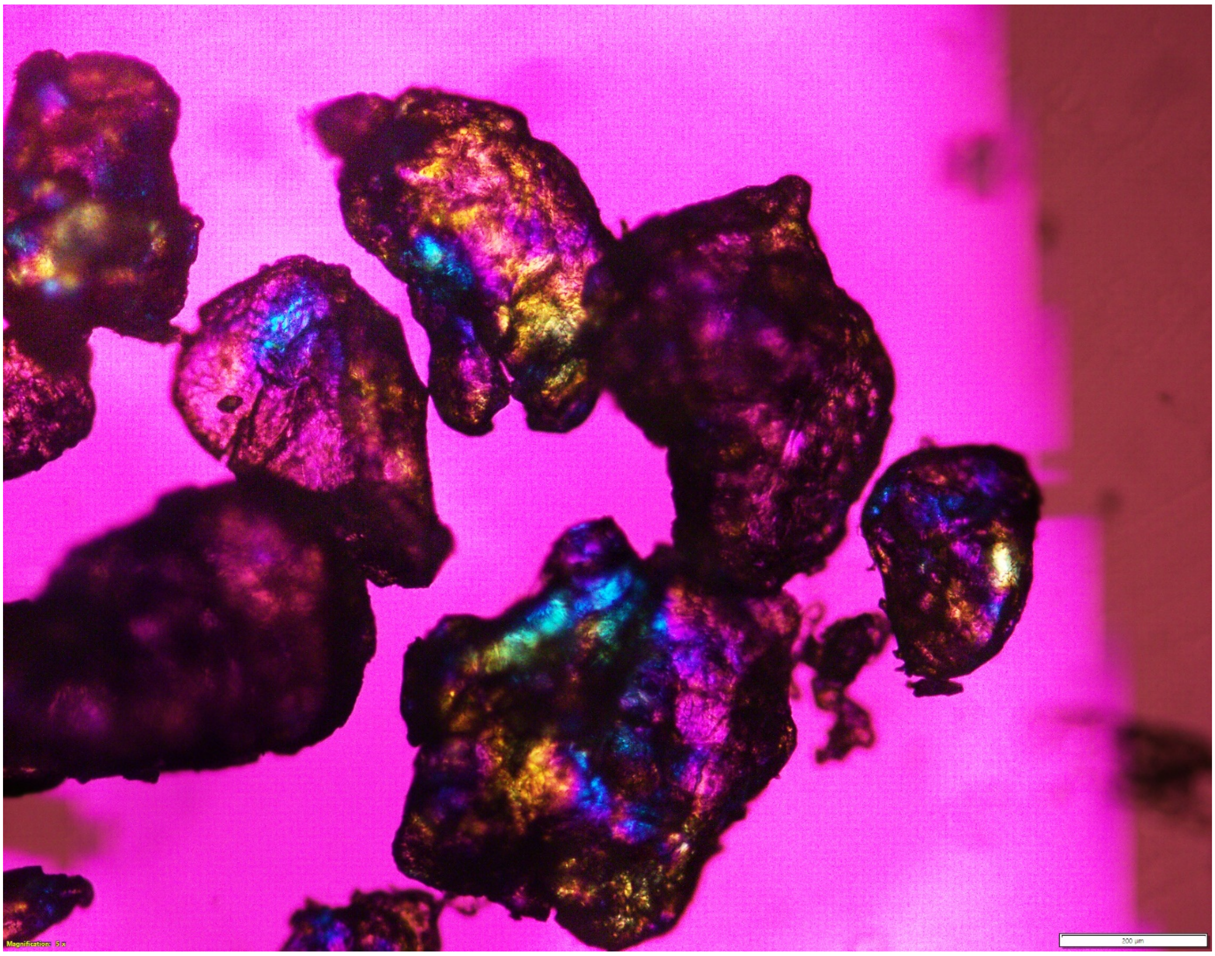

Figure S1: Microscopic image of PLA powder prior to incubation. These images served as a basis for the determination of the size and shape of the particles (magnification: 5x).

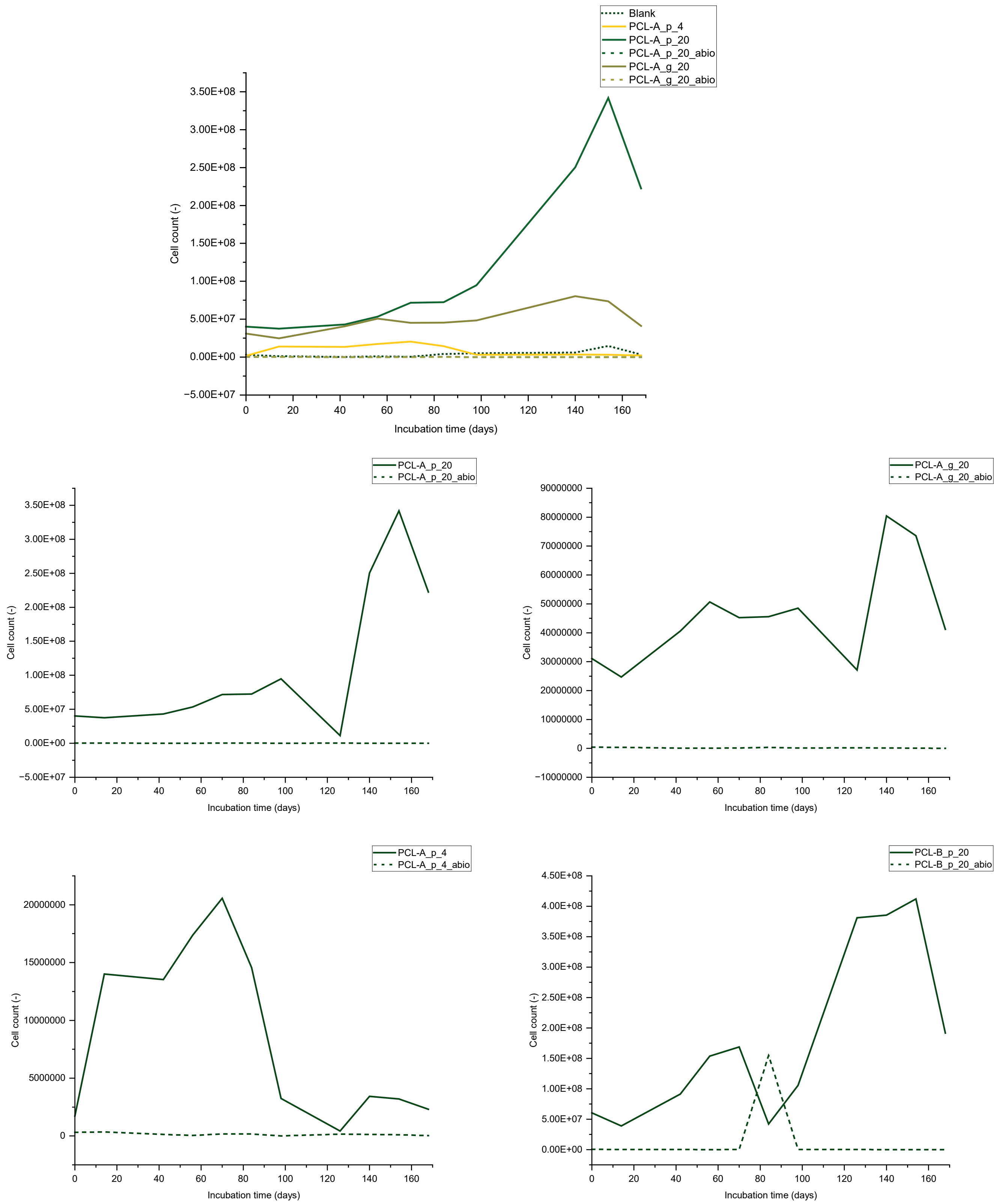

Figure S2: Cell count over time of PCL samples. Above: Comparison of all PCL samples, with "abio" indicating the cell count measured for the abiotic sample. Details are shown in the four individual graphs below. For the sample handles see manuscript Table 2.

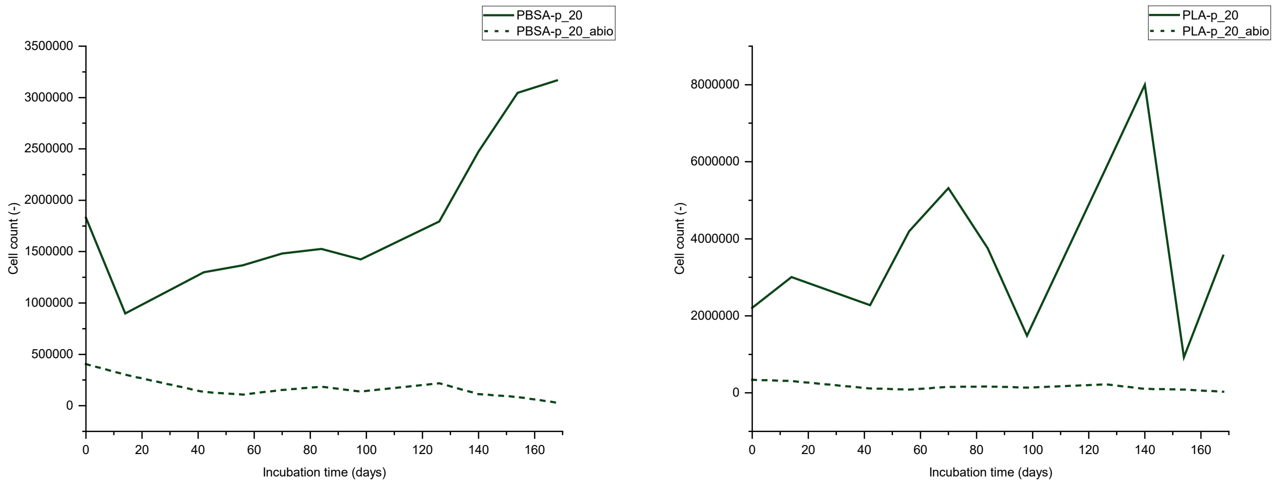

Figure S3: Cell count over time of PBSA and PLA samples. For the sample handles see manuscript Table 2.

Supplementary note 5: LCIA results of the case study

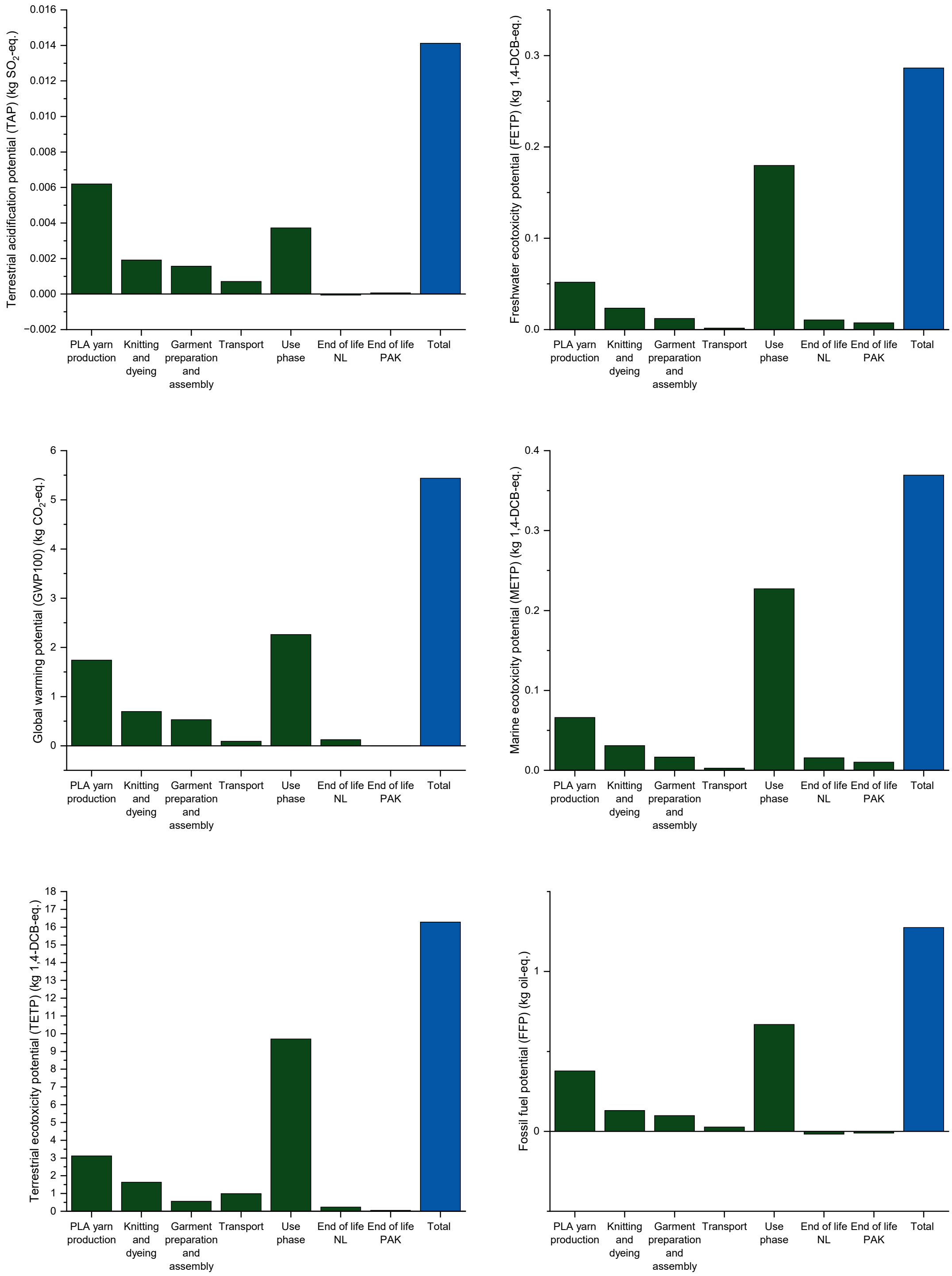

Figure S4: Results of the life cycle impact assessment (midpoint impact categories 1-6) of the case study, considering the functional unit as “using a sports shirt weekly over a period of one year in the Netherlands in 2023”.

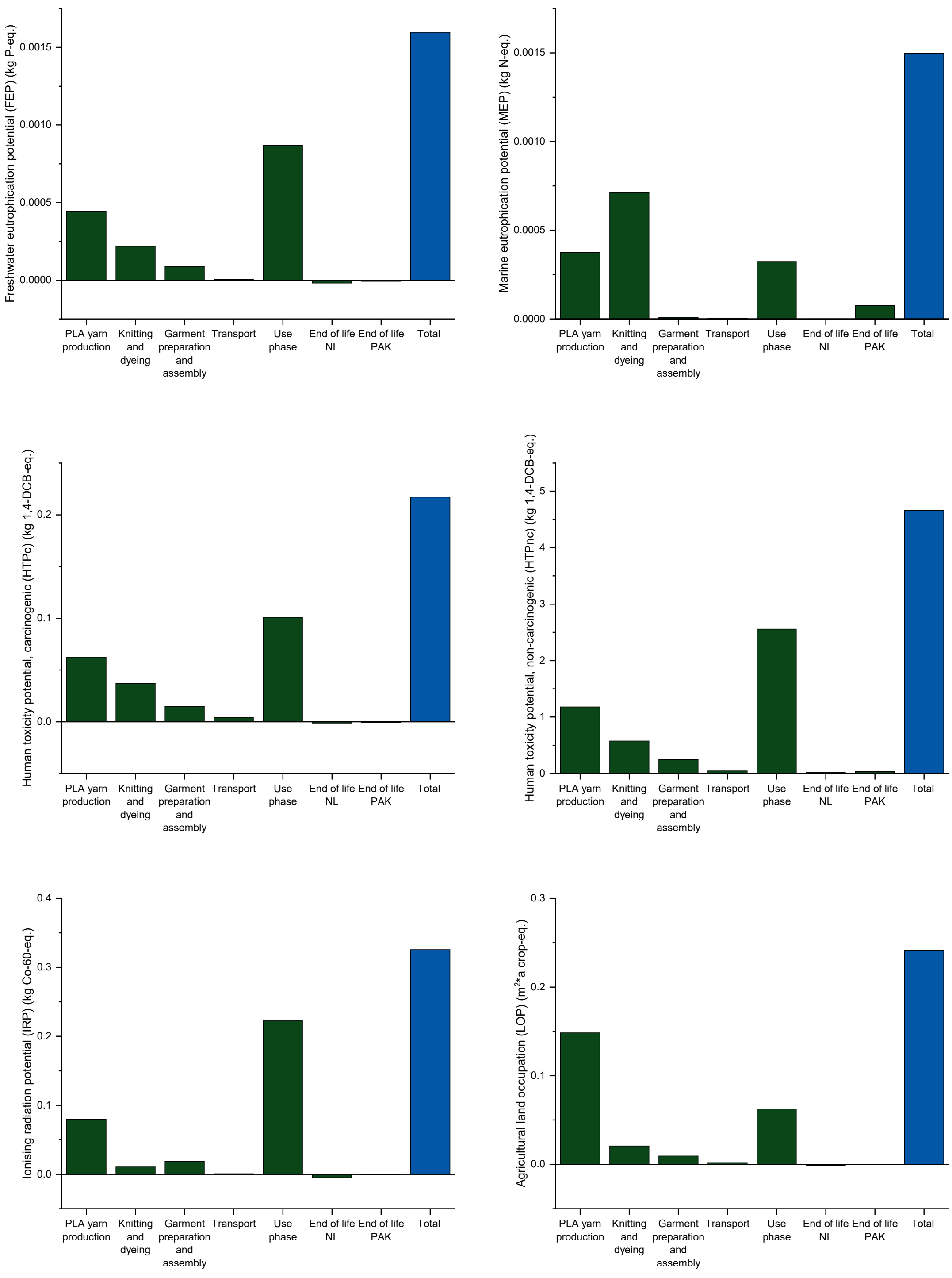

Figure S5: Results of the life cycle impact assessment of the case study, (midpoint impact categories 7-12), considering the functional unit as "using a sports shirt weekly over a period of one year in the Netherlands in 2023".

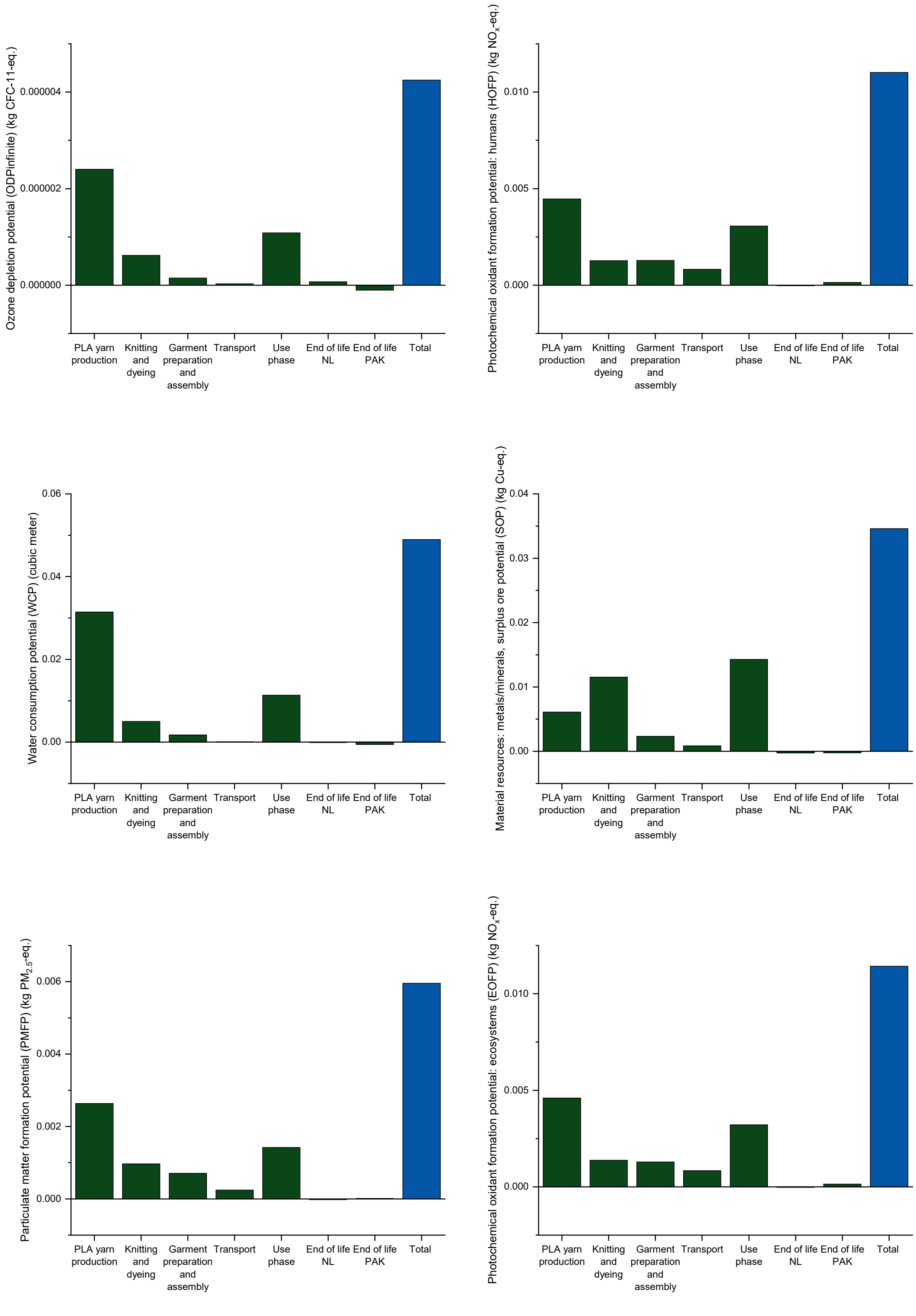

Figure S6: Results of the life cycle impact assessment of the case study (midpoint impact categories 13-18), considering the functional unit as “using a sports shirt weekly over a period of one year in the Netherlands in 2023”.

Supplementary note 6: Correction factor reasoning

As stated in the manuscript in Section 3, we propose the use of the correction factor f_{corr} (see Eq. (7) in the manuscript) to estimate the surface degradation-related mass loss when only degradation data for macroplastic samples can be found in the literature. This could avoid the underestimation of the degradation time which was discussed in the manuscript.

The correction factor is based on the ratio between the surface-area-to-volume ratios of the micro and the macro particle and aims to correct the order of magnitude of the resulting SSDR. For spheric particles of PCL we found the exponential factor of 2/3 to describe the ratio in the best way. The exponential factor could be influenced by the particle shape and ratio of bulk to surface degradation speed. To further develop the correction factor, the exponential factor needs to be tested for other particle sizes and shapes as well as for other polymers. By employing this correction factor, degradation data from literature that only consider larger particles, could still be used without overestimating the degradation rate and therefore underestimating the residence time and impact of the microplastic particle.

To determine the SSDR of the microplastic, which is necessary for the fate factor, the corrected mass loss would then be used in Eq. (4) of the manuscript. The authors want to emphasize that the altered mass loss does not represent a physically correct figure but serves as a conservative approximation of the actual specific surface degradation rate that would be present for a microplastic particle. An example of the calculation is shown below in the case of PCL grade A. The approach needs to be verified through a greater sample size.

Eq. (8) and (9) (see manuscript) are used to determine the correction factor and the corrected mass loss, considering the data for the PCL granulate:

$$f_{corr,PCL\ grade\ A} = \left(\frac{d_{micro}}{d_{macro}}\right)^{\frac{2}{3}} = \left(\frac{132\ \mu m}{1751\ \mu m}\right)^{\frac{2}{3}} = 0.179$$

$$\frac{\Delta m}{m_0}_{corr} = f_{corr} \times \frac{\Delta m}{m_0}_{macro} = 0.179\ \times 0.26\ =\ 0.047$$

The corrected mass loss is used in Eq. (4) from the manuscript:

$$\mathrm{v_{d,PCLcorrected}} = \frac{1}{2}\frac{\mathrm{d_0}}{\mathrm{t}}\left(1 - \sqrt[a]{1 - \frac{\Delta m}{m_0}}\right) = \frac{1}{2}\frac{1751\ \mu m}{182\ \mathrm{d}}\left(1 - \sqrt[3]{1 - 0.047}\right) = 0.076\frac{\mu m}{d}$$

$$= 27.644\ \frac{\mu m}{a}$$

The resulting SSDR of 27.644 µm/a has the same order of magnitude as the SSDR directly obtained through the experiments (31.795 µm/a).

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