Journal of Cleaner Production 538 (2026) 147217

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Regionalized characterization factors for microplastic emissions in life cycle assessment considering multimedia fate modelling

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HIGHLIGHTS

- CFs are available for marine, freshwater and terrestrial ecosystems.
- 2 approaches are followed: a surface-based approach and a species-based approach.
- Characterization Factors are regionalized across 8 global regions.
- A fate model is developed using SimpleBox4Plastics, adapted to align with USEtox.
- Fate Factors are proposed for 14 polymers, 5 sizes and 9 compartments on 2 scales.

ARTICLE INFO

Keywords:
Life cycle impact assessment
Microplastics
Characterization factors
Fate factors
Ecosystem quality

ABSTRACT

Microplastics released into the environment represent a threat to marine, freshwater, and terrestrial ecosystems. Current Life Cycle Impact Assessment (LCIA) methods inadequately address plastic litter, leading to an underestimation of the overall impact of plastic products on ecosystem quality. This study contributes to the MarILCA working group's efforts to incorporate plastic litter impacts into LCIA by investigating microplastic emissions across various environmental compartments and on three different types of ecosystems: Marine, Freshwater and Terrestrial.

Regionalized multimedia Characterization Factors (CFs) are calculated following two different approaches: 1- the *surface* approach, indicating the proportion of species lost over an area (in PDF·m^2·yr/kg) and 2- the *species* approach, quantifying the proportion of species lost from the global ecosystem (in PDF·yr/kg or species·yr/kg). They are calculated for midpoint and endpoint levels and focus on physical effects on biota. A fate model based on SimpleBox4Plastic adapted to USEtox is developed to characterize the fate of 14 different polymers across 5 sizes and 9 environmental compartments on continental and global scales in 8 world regions. Fate Factors (FFs) are computed and combined with Exposure and Effect Factors (EEFs) for terrestrial, aquatic, and sedimentary species, alongside Species Distribution Factors (SDFs). The developed CFs are tested in an illustrative example that assesses the impacts of biodegradable and non-biodegradable agricultural mulch film on ecosystem quality.

The endpoint CFs calculated range from 1.87E-04 and 2.95E+04 PDF·m^2·year/kg$_{emitted}$ for the surface approach and 1.57E-19 and 5.14E-08 PDF·year/kg$_{emitted}$ for the species approach. Low-density microplastics (MPs) exhibit similar CFs compared to high-density MPs, but for different reasons. Low-density MPs tend to accumulate in the water column, where the EEF is higher due to higher exposure via feeding, while high-density MPs accumulate in sediments, where the concentration of species is greater. Larger size microplastic emissions typically correspond to higher CFs due to longer degradation times. The species approach has a higher influence on the variation of CFs across regions. Case study results indicate that physical effects on biota exhibit a small contribution to ecosystem quality (0.34–2.40 % of the overall impact) for the different mulch film scenarios.

Abbreviations: CF, Characterization Factor; EEF, Exposure and Effect Factor; EF, Effect Factor; EPS, Expanded Polystyrene; FF, Fate Factor; HDPE, High Density Polyethylene; LDPE, Low Density Polyethylene; MP, microplastic; PA, Polyamide; PAN, Polyacrylonitrile; PBAT, Polybutylene adipate terephthalate; PAF, Potentially Affected Fraction of species; PDF, Potentially Disappeared Fraction of species; PET, Polyethylene Terephthalate; PHA, Polyhydroxyalkanoate; PLA, Polylactic Acid; PP, Polypropylene; PS, Polystyrene; PVC, Polyvinyl Chloride; SB4P, SimpleBox4Plastic; SDF, Species Distribution Factor; SSDR, Specific Surface Degradation Rate; TRWP, Tire and Road Wear Particles.

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https://doi.org/10.1016/j.jclepro.2025.147217
Received 16 November 2024; Received in revised form 24 November 2025; Accepted 28 November 2025
Available online 15 December 2025

The developed CFs can be integrated into emission inventories, enhancing LCAs of plastic products and facilitating informed decisions regarding plastic use.

1. Introduction

Plastic pollution has become one of the most pressing environmental issues of our time, with millions of tons of plastic waste entering natural ecosystems every year (Cottom et al., 2024). This pollution leads to the growing presence of microplastics in the environment. Microplastics are small plastic particles ranging from 1 μm to 5 mm in size (Woods et al., 2021). They can enter the environment in two ways: as primary microplastics (Boucher and Friot, 2017), which are directly emitted from sources like agriculture (Huang et al., 2020; Lwanga et al., 2022), textile fibers released during laundering (De Falco et al., 2020), plastic pellet production (Kurniawan et al., 2021), utilization of personal care products (Kurniawan et al., 2021) or tire abrasion (Baensch-Baltruschat et al., 2021). Alternatively, they can enter as secondary microplastics, which result from the breakdown of larger plastic items through processes like weathering and fragmentation (Andrady, 2022). Microplastics are released globally and have the potential to disperse far beyond their point of origin. Their presence has been documented even in remote areas ranging from the depths of the ocean (Peng et al., 2018) to the summit of mountains (Allen et al., 2019; Zhang et al., 2021). They are found in all environmental compartments (air, sea water, freshwater, soil, and sediments) and can adversely affect the species that inhabit them (De Souza Machado et al., 2018; Corinaldesi et al., 2021; Li et al., 2023; Mai et al., 2024).

Current Life Cycle Impact Assessment methods, used to assess the impact of products and services from all stages of their life cycle, and to assist environmental decision-making, do not yet fully account for the effects of microplastics released into the environment. Consequently, significant efforts are underway to integrate plastic litter impacts into LCA.

This work is part of the MarILCA (Marine Impacts in LCA) framework to achieve a comprehensive assessment of the impacts of macro-, micro- and nano-plastics for different areas of protection: Human Health, Ecosystem Quality, Socio Economic Assets, Natural and Cultural Heritage (Woods et al., 2021). MarILCA's work has so far focused solely on microplastic impacts within the marine ecosystem. Corella-Puertas et al. (2023) and Saadi et al. (2025) have developed characterization factors (CFs) for the physical effects of microplastics on the marine ecosystem, including species in the water column and sediments, following an emission into aquatic compartments (freshwater and marine). However, they do not consider microplastic emissions into terrestrial or atmospheric environments, nor their impact on freshwater and terrestrial ecosystems.

Other studies have developed CFs to assess microplastics impacts on different ecosystems for several emission compartments. Schwarz et al. (2024) have developed CFs for freshwater and marine ecotoxicity thanks to Fate Factors (FFs) calculated with SimpleBox4Plastic (SB4P) (Quik et al., 2023) for emission into marine, freshwater and terrestrial compartments. Maga et al. (2022), have proposed Fate Factors based on estimations of MPs redistribution between environmental compartments found in literature and calculated degradation rates for emissions into air, soil, freshwater and marine water. However, FFs are not linked with Effect Factors (EFs) to obtain CFs. Both studies do not consider the sedimentary compartments in the water environment, thereby neglecting the impacts on sedimentary species. This is significant because sedimentary species account for 29 % of the marine ecosystem when considering only endobenthic species and 55 % when considering all organisms feeding in the sediments (Saadi et al., 2025). Piao et al. (2024) and Zhao and You (2022) have developed CFs for the freshwater ecosystem only, with the fate calculated in water and sediment compartments. Meanwhile, Saling et al. (2020) established CFs for the marine ecosystem, specifically addressing microplastic emissions from the fragmentation of larger plastic debris. Recently, Vázquez-Vázquez et al. (2025) have calculated characterization factors for the terrestrial ecosystem by developing effect factors for three polymers (LDPE, PP and PHA). These CFs must be grouped with CFs for freshwater and marine ecosystems of other studies via a simplified fate to obtain complete CFs. None of these studies provide CFs for all ecosystems simultaneously, using a fate model that considers emissions to air, terrestrial, and aquatic compartments, and also includes sediments.

This study bridges this gap by developing CFs to assess the impact of microplastics on Ecosystem Quality (EQ) for marine, freshwater, and terrestrial ecosystems while accounting for the fate of microplastics across a wide range of environmental compartments including the sediments. EQ reflects impacts on the natural environment, assessed here as species richness decline due to microplastic emissions. The CFs development is built on the methodologies proposed by Corella-Puertas et al. (2023) and Saadi et al. (2025) for the marine ecosystem and is extended to additional compartments and ecosystems. This is achieved by calculating Fate Factors using a fate model derived from SimpleBox4Plastic and adapted to the USEtox methodology, the consensus model in (eco) toxicology, ensuring better compatibility with other impact categories. The fate depends on the physical and chemical characteristics of both the polymer and the environment.

CFs are calculated for two different approaches: a surface approach and a species approach, in different units to facilitate their integration into diverse impact assessment methods. Ultimately, they are developed for 14 different polymers (EPS, PP, LDPE, HDPE, PS, PAN, PHA, PA, PLA, starch blend, PBAT, PET, PVC and TRWP), 5 sizes (1, 10, 100, 1000, 5000 μm), 1 shape (spherical), 9 environmental compartments (air, lake water, river water, sea water, their sediments, natural soil, terrestrial soil) on 2 scales (continental and global), 9 regions (North America, Latin America, Europe, Africa and Middle East, Central Asia, Southeast Asia, Northern regions, Oceania, World) and 3 ecosystems (Marine, Freshwater, Terrestrial). To illustrate the use of these CFs, they are applied to an existing case study.

2. Methods

The primary objective of this work is to calculate Characterization Factors (CFs) as described in Section 2.1. The process involves several key steps:

1. Calculation of Fate Factors (FFs) (Section 2.2) through the development of a fate model based on SimpleBox4Plastic adapted to USEtox.
2. Implementation of Exposure and Effect Factors (EEFs) (Section 2.3) sourced from the literature for organisms in three different types of environmental compartments: aquatic, sedimentary, and terrestrial.
3. Scaling of the CFs from the compartment to the ecosystem level with SDFs (e.g. marine sediment to marine ecosystem) following two different approaches:
   a. The *surface* approach (Section 2.1.1), indicating the proportion of species lost over an area (in PDF·m^2·yr/kg)
   b. The *species* approach (Section 2.1.2), quantifying the proportion of species lost from the main ecosystems (in PDF·yr/kg)
4. Calculation of default CFs for LCA practitioners (Section 2.5)
5. Testing of the developed CFs (Section 2.6) by applying them to an existing case study that compares biodegradable and non-biodegradable mulch films under Nordic conditions.

2.1. Characterization factors

The CFs calculated here represent the physical impact of microplastics on biota per kilogram of microplastics of a specific polymer and size emitted into a designated compartment.

Compartment-level CFs in $[PAF{\cdot}m^3{\cdot}day/kg_{emitted}]$ are usually computed by multiplying a Fate Factor matrix (FF) in $[kg_{in\ compartment}/(kg_{emitted}/day)]$, an Exposure Factor matrix (XF) $[kg_{bioavaiblable}/\left(kg_{in\ compartment}\right)]$ and an Effect Factor matrix (EF) in $[PAF{\cdot}m^3/(kg_{bioavailable})]$ (Owsianiak et al., 2023; Rosenbaum et al., 2007). In this study, XF and EF are represented by a combined Exposure and Effect Factor matrix EEF in $[PAF{\cdot}m^3/kg_{in\ compartment}]$ as the exposure and effect factors found in literature are not distinguished separately (Lavoie et al., 2022). The final formulation is given in Equation (1) and the structure of the compartment-level CFs matrix is illustrated in Supporting Information (SI) 1. CF is a square matrix with columns representing emission compartments, while rows correspond to receiving compartments.

$$CF_{comp} = EEF \times FF \tag{1}$$

To generate ecosystem-level CFs, for the three global ecosystems (Marine, Freshwater and Terrestrial) from compartment-level CFs, two approaches are possible and are calculated in this study.

The *surface* approach considers the Potentially Disappeared Fraction of species (PDF) over a surface. It assumes that a square meter of any local ecosystem is equivalent to another one within one of the three global ecosystems (Marine, Freshwater or Terrestrial), even if they contain a different number of species. In ecosystems with fewer species, each species may hold greater importance for the ecosystem's functioning compared to ecosystems with more species. In this case, CFs are calculated in $[PDF{\cdot}m^2{\cdot}year/kg_{emitted}]$ at endpoint level, representing the local potentially disappeared fraction of species over a surface and period.

The *species* approach, however, considers the proportion of affected or disappeared species within a global ecosystem (Marine, Freshwater or Terrestrial). It assumes that all species within a global ecosystem have the same intrinsic value regardless of their location. This implies that a local ecosystem with more species is given greater importance than one with fewer species. For this approach, the midpoint CFs are calculated in $[PAF{\cdot}day/kg_{emitted}]$ and represent the global ecosystem fraction of species affected within a period of time while the endpoint CFs are calculated in $[PDF{\cdot}year/kg_{emitted}]$ and represent the global ecosystem fraction of species disappeared within a period of time.

The choice between the two methods depends on the underlying objective: either to conserve an ecosystem area in its current state by maintaining the species richness within it (surface approach), or, in a broader perspective, to preserve the overall species diversity that exists (species approach). This choice is intrinsic to the impact assessment method to which the user wishes to integrate these CFs, and consequently, the approach with the consistent unit must be applied. A surface approach, which expresses impacts on EQ in PDF·m^2·year, is used in IMPACT World + (the update of IMPACT, 2002+, EDIP and LUCAS) (Bulle et al., 2019). In contrast, a species approach is followed by methods like ReCiPe (in species·year) (Huijbregts et al., 2017), LC-IMPACT (Verones et al., 2020) and GLAM (the Global Guidance on Environmental Life Cycle Impact Assessment Indicator) (in PDF·year) (Verones et al., in preparation).

The CFs for both approaches are computed independently for the marine, freshwater, and terrestrial ecosystems. These ecosystem-level CFs are expressed in PDF of the specific ecosystem e.g. for the marine ecosystem in PDF_{marine}.

They can then be optionally combined into a single, global CF in PDF of all ecosystems by applying an equal weighting of $\frac{1}{3}:\frac{1}{3}:\frac{1}{3}$, thereby assigning the same importance to each of the three global ecosystems. This approach follows the guidance provided by GLAM (Verones et al., in preparation). Alternatively, a different weighting scheme based on species richness or surface per ecosystem could be applied to create a globally aggregated CF, reflecting variations in species richness across ecosystems.

2.1.1. Surface approach

To calculate ecosystem-level impacts in $[PDF{\cdot}m^2{\cdot}year/kg_{emitted}]$, each row of the compartment-level matrix corresponding to receiving compartments is first divided by its volume. Next, overlapping compartments, such as the water column and sediment, are aggregated using the fraction of species that feed within them (see Section 2.4). The resulting values are multiplied by a Severity Factor (SF) equal to 1 $[PDF/PAF]$ (Oginah, 2023; Owsianiak et al., 2023) as per the latest recommendations provided by GLAM, and are divided by the number of days in a year and multiplied by the surface of each compartment. Finally, the compartments are summed by ecosystem.

With this method, midpoint indicators cannot be expressed in $[PAF{\cdot}m^3{\cdot}year/kg_{emitted}]$, as this would require multiplying CFs from overlapping compartments by the total volume of both compartments. This would disproportionately emphasize sediments, which have a much smaller volume than the water column. However, the approach is suitable when using surface area, since both compartments share the same surface. If midpoint indicators are desired using the surface approach, they could easily be calculated by using a plastic of reference and dividing the CF endpoint of any polymer with the one of the reference. We recommend PP (1um)-equivalent be used (to choose a common, small size particle). It wasn't included in the present results as a large amount of datasets is already presented.

2.1.2. Species approach

To calculate midpoint ecosystem-level impacts in $[PAF{\cdot}day/kg_{emitted}]$, compartment-level values are divided by their volume (V_{comp}) and multiplied by a Species Distribution Factor (SDF) matrix $[-]$ (Saadi et al., 2025) (Equation (2)). The Species Distribution Factor represents the fraction of species living or feeding in each compartment for each ecosystem. The different factors' matrices are explained in Section 2.4.

$$CF_{mid\ PAF{\cdot}day} = \frac{CF_{comp}}{V_{comp}} \times SDF \tag{2}$$

To transition to the endpoint level in $[PDF{\cdot}year/kg_{emitted}]$, the midpoint ecosystem-level CFs are multiplied by the Severity Factor and divided by the number of days in a year (Equation (3)).

$$CF_{end\ PDF{\cdot}year} = CF_{mid\ PAF{\cdot}day} \times \frac{SF}{365} \tag{3}$$

Endpoint CFs for the species approach are also available in $[species{\cdot}year/kg_{emitted}]$ in SI 2. They are calculated by multiplying the ecosystem-level impacts by the total number of described species for each ecosystem (Goedkoop et al., 2013). As an exception, for this unit, globally aggregated CFs are calculated by summing the CFs of each ecosystem, in line with the method's philosophy, which focuses on the absolute number of species affected rather than the fraction of species.

2.2. Fate factors

Fate Factors (FFs) represent the mass of pollutant in a receiving environmental compartment following an emission flow in a source compartment (Rosenbaum et al., 2007). They are expressed in $[kg_{in\ compartment}/(kg_{emitted}/day)]$. When the emission and the receiving compartments are the same, FFs indicate the residence time of the pollutant in these compartments, measured in $[days]$. These factors are derived from transfer rates calculated through a fate model.

2.2.1. Development of a fate model based on SimpleBox4Plastic

A fate model serves in evaluating the pathways and ultimate destinations and residence time of microplastics released into specific

environmental compartments. One of the objectives of this study is to develop Fate Factors through a fate model for microplastics that meet the needs of LCIA methods, i.e., a simplified model that can be used to calculate fate factors and that closely aligns with the consensus model for (eco)toxicology in LCA USEtox (Rosenbaum et al., 2008). The existing fate model SimpleBox4Plastic (Quik et al., 2023) already partially meets these criteria and requires a few adjustments to align fully.

SimpleBox4Plastic calculates the final concentrations of spherical plastic nano and micro particles in various environmental compartments following their emission into a specific compartment. The model provides concentrations for three distinct particle forms, referred to as species: free, aggregated, and attached, to account for the hetero-agglomeration and heteroattachment of plastic particles with natural particles. The calculations for the different mechanisms responsible for agglomeration and attachment, transport, or removal of plastic particles are based on particle properties such as size and density, as well as landscape settings (e.g., area, depth, rain rate, runoff fraction, etc.). SB4P includes air, freshwater, sea water, sediment, and soil compartments across three different scales: regional, continental, and global.

A fate model (Fig. 1) is therefore developed based on SB4P by making modifications to the original model. Several mechanisms are also adjusted thanks to newer data. The different modifications are listed below and explained in SI 1:

a. The scale is reduced to two levels—continental and global—and the other soil compartment is redistributed between agricultural and natural soils to align with USEtox structure.
b. The degradation mechanism is adjusted by calculating degradation rates using Specific Surface Degradation Rates (SSDR) following the methodology of Chamas et al. (2020) and Corella-Puertas et al. (2022). When available, compartment-specific SSDRs for each polymer are used (3 out of 14 for sediment, 8 out of 14 for soil); otherwise, the default SSDRs for water are applied (see SI 3). The fragmentation mechanism is eliminated.
c. The runoff mechanism is updated to include an interception mechanism.
d. The sedimentation rate is updated to better reflect the effects of biofouling.
e. The air and cloud water compartments are merged following the methodology ofSalieri et al. (2019).
f. The three forms of plastic particles—free, aggregated, and attached—are grouped into a single form following the methodology of Salieri et al. (2019).
g. The model is regionalized.

2.2.2. Fate factor matrix

The transfer rates calculated through the fate model are placed into a transfer rate matrix, called K. K is a square matrix with columns representing emission compartments and rows representing receiving compartments. The values within the matrix indicate the transfer rates from emission compartments to receiving compartments. The diagonal elements of the matrix represent the removal rates, which include both the rates of transfer out of the compartment and the internal removal mechanisms, such as degradation. The FF matrix is calculated by taking the negative of the inverse of the K matrix (Equation (4) & Equation (5)) (Rosenbaum et al., 2007).

$$\overline{FF} = -\overline{K^{-1}} \tag{4}$$

$$\overline{FF} = -\begin{bmatrix} -k_{a.C,tot} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \\ k_{a.C\to lw.C} & -k_{lw.C,tot} & 0 & 0 & k_{lw.sed.C\to lw.C} & 0 & 0 & k_{nat.soil.C\to lw.C} & k_{agr.soil.C\to lw.C} & \\ k_{a.C\to rw.C} & k_{lw.C\to rw.C} & -k_{rw.C,tot} & 0 & 0 & k_{rw.sed.C\to rw.C} & 0 & k_{nat.soil.C\to rw.C} & k_{agr.soil.C\to rw.C} & \\ k_{a.C\to sw.C} & 0 & k_{rw.C\to sw.C} & -k_{sw.C,tot} & 0 & 0 & k_{sw.sed.C\to sw.C} & 0 & 0 & \\ 0 & k_{lw.C\to lw.sed.C} & 0 & 0 & -k_{lw.sed.C,tot} & 0 & 0 & 0 & 0 & \cdots \\ 0 & 0 & k_{rw.C\to rw.sed.C} & 0 & 0 & -k_{rw.sed.C,tot} & 0 & 0 & 0 & \\ 0 & 0 & 0 & k_{sw.C\to sw.sed.C} & 0 & 0 & -k_{sw.sed.C,tot} & 0 & 0 & \\ k_{a.C\to nat.soil.C} & 0 & 0 & 0 & 0 & 0 & 0 & -k_{nat.soil.C,tot} & 0 & \\ k_{a.C\to agr.soil.C} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -k_{agr.soil.C,tot} & \\ & & & & \cdots & & & & & \end{bmatrix}^{-1} \tag{5}$$

In the end, FF matrices are computed for 14 different polymers at 5 sizes and for 8 different regions of the world. The FFs are calculated at steady state (integrated to infinite time).

2.3. Exposure and effect factors

2.3.1. Exposure and effect factor matrix

The combined Exposure and Effect Factors matrix (EEF) is a matrix composed of Exposure and Effect Factors (EEFs). In this context, the exposure refers to the concentration of microplastics available to species for an emission in a given compartment, while the effect represents the fraction of species potentially affected by this exposure (Lavoie et al., 2022).

The EEF matrix is a square matrix (Equation (6)). EEFs are placed along the diagonal. The EEF for water (EEF_w) is applied to the result of the fate in aquatic compartments, the EEF for sediment (EEF_{sed}) in sedimentary compartments, and the EEF for terrestrial systems (EEF_{ter}) in terrestrial compartments.

$$\overline{EEF} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \\ 0 & EEF_{aq} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \\ 0 & 0 & EEF_{aq} & 0 & 0 & 0 & 0 & 0 & 0 & \\ 0 & 0 & 0 & EEF_{aq} & 0 & 0 & 0 & 0 & 0 & \\ 0 & 0 & 0 & 0 & EEF_{sed} & 0 & 0 & 0 & 0 & \cdots \\ 0 & 0 & 0 & 0 & 0 & EEF_{sed} & 0 & 0 & 0 & \\ 0 & 0 & 0 & 0 & 0 & 0 & EEF_{sed} & 0 & 0 & \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & EEF_{ter} & 0 & \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & EEF_{ter} & \\ & & & & & \cdots & & & & \end{bmatrix} \tag{6}$$

2.3.2. Values of exposure and effect factors

The EEFs for the different compartments—water, sedimentary and terrestrial—were developed by other authors for use in LCIA. They are calculated from a hazardous concentration of 20 % (HC20), derived from a species sensitivity distribution (SSD) of effect concentrations of 10 % (EC10) as recommended by GLAM (Owsianiak et al., 2023).

The EEF for water is 1067.51 $[PAF_w \cdot m^3 / kg_{emitted}]$. This factor was initially developed by Lavoie et al. (2022) and subsequently updated by Corella-Puertas et al. (2023). It is derived from 33 data points from virgin polymers and chronic exposure, except for fish species, for which one acute data was used and converted to chronic-equivalent (Lavoie

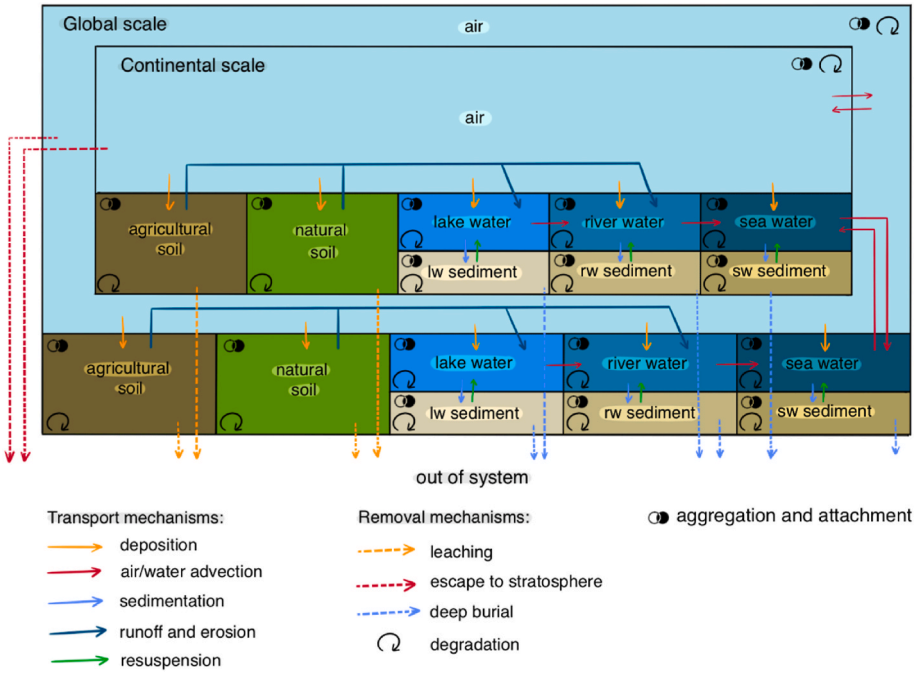

Fig. 1. Diagram of the fate model and its different mechanisms.

et al., 2022). The sedimentary EEF is 16.17 $[PAF_{sed} \cdot m^3 / kg_{emitted}]$ and is calculated based on 54 virgin polymer data points for marine and freshwater sediments (Saadi et al., 2025). Finally, the EEF for terrestrial compartments, developed by Tunali and Nowack (2025), is valued at 0.54 $[PAF_{ter} \cdot m^3 / kg_{emitted}]$. This value was preferred over those developed by Vázquez-Vázquez et al. (2025), who did not apply conversion factors to derive effect factors in terms of particle mass from effect data expressed in number of particles. It was calculated for a wide range of polymers, shapes, and sizes, rather than being specific to a single polymer. Moreover, this factor is based on 29 chronic data points for virgin polymers, except for one value, and does not rely on HONEC data.

$$\overline{SDF} = \begin{bmatrix} 0 & 0 & 0 & SDF_{sw.C} & 0 & 0 & SDF_{sw.sed.C} & 0 & 0 & \\ 0 & SDF_{lw.C} & SDF_{rw.C} & 0 & SDF_{lw.sed.C} & SDF_{rw.sed.C} & 0 & 0 & 0 & \dots \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & SDF_{nat.soil.C} & SDF_{agr.soil.C} & \end{bmatrix} \quad (7)$$

2.4. Species Distribution Factors

2.4.1. Species Distribution Factor matrix

The Species Distribution Factor matrix (Equation (7)) represents the fraction of species found in a compartment for a specific ecosystem. Columns represent the different emission compartments and rows the specific ecosystems: Marine, Freshwater, Terrestrial. This matrix is developed by Saadi et al. (2025) to scale compartment-level CFs to ecosystem-level CFs. In Saadi et al. (2025), it is used to represent impacts on the marine ecosystem as a whole, where equal value is given to every marine species. EEFs of the water column and sediments are scaled from an affected fraction of water or sedimentary species (PAF_w or PAF_{sed} respectively) to an affected fraction of marine species (PAF_{marine}). This method is applied directly in this study to obtain CFs in $PDF_{marine} \cdot year$ for the marine ecosystem and adapted to the freshwater and terrestrial ecosystems to group PDF of river, lake, river sediment and lake sediment in PDF for the whole freshwater ecosystem and PDF of natural soil and agricultural soil in PDF for the whole terrestrial ecosystem.

2.4.2. Calculation of Species Distribution Factors

Species Distribution Factors are calculated for each compartment of each ecosystem. The final SDFs and the details of their calculations are available in SI 1 and SI 4. For each ecosystem, a fraction of species in the different compartments that composed the ecosystem is calculated but also a fraction of species in the continental and global scales. This last fraction is regionalized for the 8 world regions. These fractions are based on either where the species live or feed depending on the environment.

2.4.2.1. Marine ecosystem. The fraction of species in water and sediment for the marine ecosystem is taken from (Saadi et al. (2025) and based on the feeding environment of the species. This fraction is also used in the surface approach to aggregate the marine water column and sediments. The fractions of species at the continental scale and the global scale are based on the habitat and are regionalized. Finally, SDFs are calculated by multiplying the fraction of species feeding in either the sediment or the water column and the fraction of species living in either the continental or the global scale.

2.4.2.2. Freshwater ecosystem. The same methodology is applied to the freshwater ecosystem. Three different fractions of species are needed:

- The fractions of species feeding in either sediment or water column. As the one for the marine ecosystem, this fraction is also used in the surface approach to aggregate the water column and the sediment.
- The fractions of species living in either lake water or river water (only for the species approach)
- The fractions of species living in either the continental scale or the global scale depending on the region (only for the species approach)

2.4.2.3. Terrestrial ecosystem. Two different fractions of species are needed for the terrestrial ecosystem (both only for species approach):

- The fractions of species living in natural soil or agricultural soil
- The fractions of species living in either the continental scale or the global scale depending on the region

2.5. Default characterization factors

2.5.1. Default region

World default characterization factors are developed for LCA practitioners to use when the region of emission is unknown. These CFs are based on the existing CFs for the different regions of the world calculated in this study and aggregated with a weighted average using emissions inventory of plastic pollution developed by Cottom et al. (2024) as weights. Due to the limited availability of microplastic data, and the generation of microplastics from macroplastics, macroplastic emissions data are used (see SI 2).

2.5.2. Default polymer

In this study, low-density polymers refer to polymers with density lower than 1 g/cm^3 thus, lower than water: EPS, PP, LDPE, HDPE. On the contrary, high-density polymers refer to polymers with density superior to 1 g/cm^3: PS, PAN, PHA, PA, PLA, starch blend, PBAT, PET, PVC and TRWP.

CFs are calculated for three types of default polymers:

- Low-density default polymer: used when the specific polymer type is unknown, but is known to have a density below 1 g/cm^3.
- High-density default polymer: used when the polymer type is unknown, but is known to have a density above 1 g/cm^3.
- Unknown-density default polymer: used when neither the polymer type nor its density is known.

The method for calculating CFs for these default polymers follows the same approach as detailed in Section 2.5.1. The CFs are derived from existing CFs for individual polymers, weighted by the global production shares of each polymer type as reported by Geyer et al. (2017). If no polymer production was reported, its weight is set to zero. The more widely produced a polymer is, the greater its influence on the default CF. The weighting is available in SI 2.

2.5.3. Default size

Default sizes are provided for cases where the size of emitted microplastics is unknown to the LCA practitioner. These are based on Corella-Puertas et al. (2023): a diameter of 1000 μm for microbeads, a thickness of 100 μm for film fragments, and a diameter of 10 μm for cylinders or microfibers.

2.6. Case study

The CFs developed are tested as an illustrative example in a case study conducted by De Sadeleer and Woodhouse (2024), which compares biodegradable and non-biodegradable agricultural mulch films used for growing lettuce on 1 ha under Nordic conditions. The case study evaluates three scenarios: the use of a non-biodegradable LDPE mulch film (scenario 1) and two biodegradable mulch films, one made of 70 % PBAT and 30 % corn starch (scenario 2) and another composed of 30 % PBAT and 70 % corn starch (scenario 3). This case study was selected because it involves microplastic emissions in a terrestrial environment, resulting in their distribution across multiple environmental compartments—such as lakes, rivers, marine waters, and their respective sediments—thereby illustrating the impacts of a plastic product across all three major ecosystems: terrestrial, freshwater, and marine. Moreover, the study's geographic focus made it a relevant case for applying our regionalized CFs. Initially, the case study covers several environmental impact categories, with plastic pollution potential assessed separately through material flow analysis due to the absence of relevant characterization factors. This work adds the potential physical effects on biota impacts of microplastics at the endpoint level. Details on the original case study and its assumptions can be found in SI 1; calculations are in SI 5.

3. Results and discussion

3.1. Fate factors

Fate Factors (FFs) are calculated for 14 different polymers across 5 size categories, 1 spherical shape, 9 environmental compartments at 2 scales, and 9 regions, including the default region 'World'. All FFs are available in SI 3. This analysis focuses exclusively on FFs for emissions into continental air, lake water, river water, sea water, natural soil, and agricultural soil, as these compartments are more likely to be the ones where emissions occur. However, all receiving compartments are included in the assessment. Emissions to sediment compartments could typically result from the breakdown of macroplastics that have already settled. Factors for emissions on a global scale are generally not applicable, except for those in global sea water within the 'World' region, which may represent microplastic emissions from fishing gear.

FFs found in this study range from 0 to 1.86E+06 $kg_{in\ compartment}$/($kg_{emitted}$/days), depending on region, polymer, size, emission compartment, and receiving compartment. The highest FFs are observed for HDPE, a low-density polymer, when emitted into continental sea water, with the receiving compartment being global sea water.

Fig. 2 illustrates the distribution of microplastics found in the different receiving compartment at steady state after emission into a specific compartment for low- and high-density polymers at minimum (1 μm) and maximum (5000 μm) size.

We observe that low-density polymers are more mobile than high-density polymers. The fate is largely determined by the sedimentation rate, polymers that have a higher sedimentation rate tend to remain near their source compartment by settling as soon as they reach a water compartment. Settling velocity depends on both the size and density of the polymer. Larger, high-density polymers settle faster than smaller, low-density ones. As a result, only a very small amount of large high-density polymers emitted in freshwater or soil is found in global sea water or its sediment after steady-state while almost all large low-density polymers accumulate in global sea water.

The fate is also influenced by the degradation rate of the polymer which is influenced by the size of the polymer and its surface degradation rate. Smaller plastic particles are less likely to transfer to other compartments than larger particles, as they tend to degrade before reaching those compartments. Microplastics with high degradation rates, such as biodegradable polymers (primarily starch blends, PHA, and PBAT), will also exhibit a lower residence time in the environment.

3.2. Characterization factors

Characterization factors (CFs) for physical effects on biota are calculated at endpoint level for the same polymers, size categories, shapes, emission compartments, and regions as the fate factors. All endpoint CFs calculated with the two approaches explained in the methodology are provided in SI 2. As with the FFs, this analysis focuses exclusively on CFs for emissions into continental air, lake water, river,

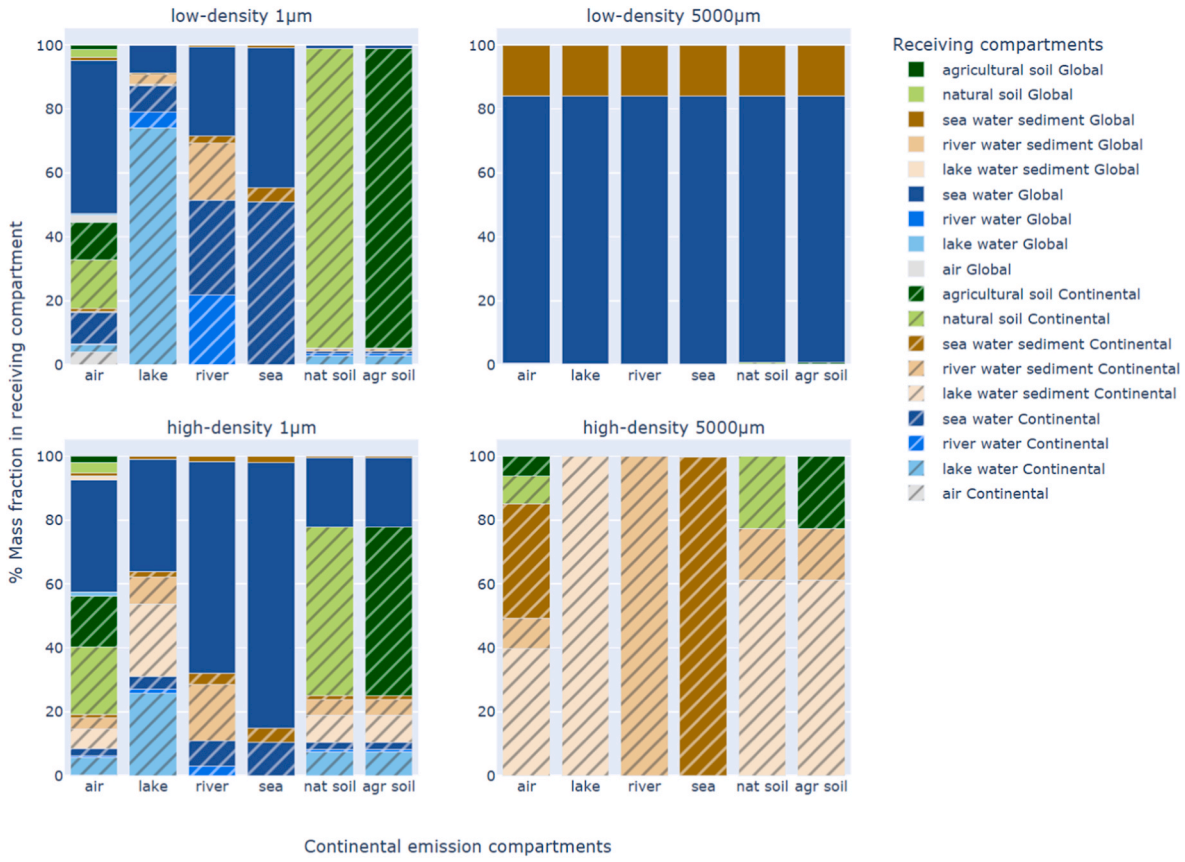

Fig. 2. Mass fraction of microplastics in percentage found in receiving compartment for an emission in a continental compartment for the World region and default low-density and high-density polymers and for the minimum (1 µm) and the maximum sizes (5000 µm).

sea water, natural soil, and agricultural soil.

3.2.1. Surface approach

3.2.1.1. Polymer type and size. The endpoint CFs range between 1.87E-04 and 2.95E+04 PDF·m^2·year/kg$_{emitted}$. Fig. 3 illustrates the intervals of endpoint CF values for the different polymers and sizes in the default region 'World'. The bars represent the range of values corresponding to the different emission compartments. The polymers with the highest CFs are either high-density or low-density polymers with the lowest calculated degradation rates as they will remain longer in the environment while the lower CFs correspond to biodegradable high-density polymers such as PHA and starch blend which have fast degradation rates.

Regarding density, high-density particles tend to settle into sediments, while low-density particles remain suspended in the water column. High-density polymers will affect primary sedimentary species while low-density polymers will affect more water column species. The EEF of sedimentary species is lower than the one of water column species but the greater species density and limited volume of sediment lead to CFs of similar order of magnitude for both compartments.

In terms of size, larger emitted MPs typically correspond to higher CFs linked with their longer degradation time as degradation rate is size-dependent (see SI 1). This is not the case for some high-density polymer/size combinations (PLA, PAN) that exhibit the lowest degradation rates of high-density polymers in the sediment. However, it is important to note that the differences between polymer sizes in this study are based on the fate of microplastics, not on their effects, for which we use a single factor per ecosystem, independent of the size of the plastic particles.

3.2.1.2. Ecosystems and emission compartments. Fig. 4 illustrates the different CFs calculated in PDF·m^2·year/kg for all polymers, emission compartments and ecosystems affected for the minimum (1 µm) and maximum size (5000 µm).

For the largest size (5000 µm) of low-density polymers, the CFs observed show consistently higher impacts on the marine ecosystem across all emission compartments. As discussed in Section 3.1 and 2.3, this pattern can be attributed to fate, exposure, and effect factors: low-density polymers tend to accumulate in global sea water, especially as particle size increases, where EEF is most significant.

For the smallest size (1 µm) of low-density polymers, the most impacted ecosystem depends on the emission compartment but is often the freshwater ecosystem. This can be explained by the short residence time of small particles, which limits their ability to reach the marine environment.

CFs are higher for emissions in rivers compared to lake water whereas the residence time of microplastics is longer in lakes than in rivers. Rivers are shallower than lakes, and hence a larger depth is used to collapse the volumetric PDF into a surface-area PDF. This could be interpreted as a way to represent a "higher concentration of PDF" in the river versus the lake, keeping in mind that the PDF refers to a fraction of the species present in that volume, and does not represent the absolute number of species in any way.

Regarding the largest size of high-density polymers, CFs are the highest for emissions in sea water with an impact on the marine ecosystem. For the smallest polymers, CFs are higher for the freshwater ecosystem for an emission in river or lake water. Particles emitted into compartments other than sea water have a low impact on the marine ecosystem, as they tend to settle quickly in the first water compartment they encounter (lake water or river).

More generally, when emissions occur in soil or freshwater compartments, low-density polymers are more likely to reach marine

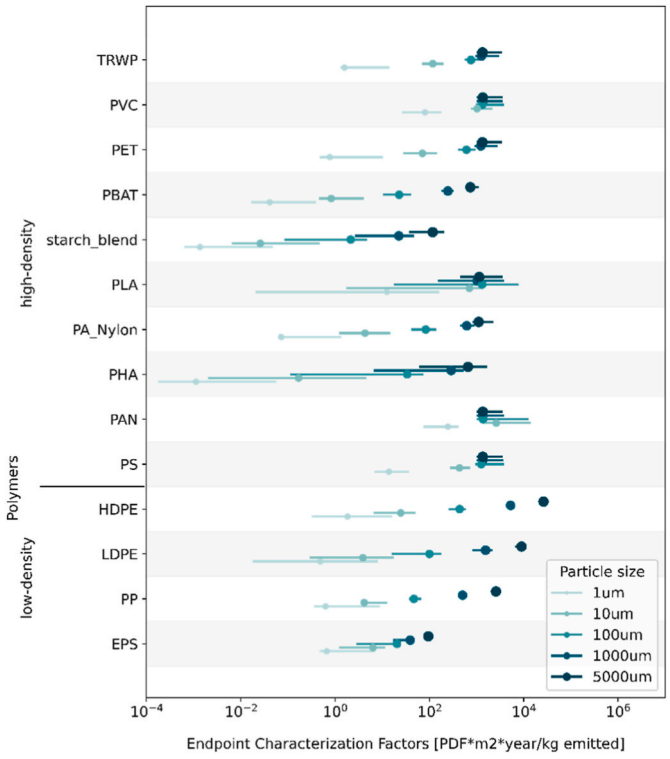

Fig. 3. Endpoint characterization factors (CFs) for physical effects on biota for emissions into air, lake water, river water, sea water, natural soil, agricultural soil at continental scale and for different polymers at different sizes calculated in PDF·m^2·year/kg$_{emitted}$. Bars represent the range of characterization factors for emissions in the different compartments and the point the median value of the CFs.

environments except for very small particles, while high-density polymers tend to settle in rivers or lakes and are less likely to be transported to marine compartments. Consequently, high-density polymers emitted to soil or freshwater have a greater impact on freshwater ecosystems and a lower impact on marine ecosystems compared to low-density polymers.

3.2.1.3. Regionalization interpretation. Endpoint CFs calculated in PDF·m^2·year/kg show low variations between the different regions of the world, as every surface of ecosystem is given the same weight. A figure showing the distribution of CFs for the different regions is available SI 1. Even if the variations are low, we can note some differences in the CFs for emissions of low-density polymers emitted in soil across the regions. This is mainly explained by the differences in the fraction of runoff and precipitation. Regions that have low precipitation and fraction of runoff will have more MPs retained in soil and less going into freshwater and marine compartments where the EEF is a ten thousand times higher than in soil.

3.2.1.4. Sources and magnitude of CF variability. In the surface approach, the variation of the CF based on density, size, and emission compartments can be compared. The greatest variation across different polymers for the same size and emission compartment is 6 orders of magnitude, occurring for the smallest size emitted into air and soil compartments. The largest CF variation across different sizes for a specific polymer is observed with PHA, spanning 7 orders of magnitude. The greatest CF variation across emission compartments is 4 orders of magnitude, seen for PLA at a size of 1 μm. Hence the size leads to the largest variability, followed by the polymer type (linked to density and degradation rate) and the emission compartment.

3.2.2. Species approach

3.2.2.1. Species Distribution Factors. Species Distribution Factors are calculated for each compartment of each scale for the 8 different regions. All SDFs can be found in SI 4. For all ecosystems, SDFs are higher at the global scale than at the continental scale, as the number of species is higher in the rest of the world than in one specific continent.

In the marine ecosystem at the continental level, SDFs are slightly higher in sediments ranging between 2 % and 21 % across continents (and between 34 % and 53 % at global scale) compared to the water column, ranging from 2 % to 17 % at continental scale (and from 28 % to 43 % at global scale). Southeast Asia has the highest SDFs at the continental scale, indicating that this region supports the greatest diversity of marine species. Conversely, Europe has the lowest SDFs, meaning it has the fewest marine species.

For the freshwater ecosystem, SDFs are higher in river sediments (3 %–15 % at continental scale and 36 %–49 % at global scale), followed by river water (1 %–7 % and 15 %–21 %), lake water sediments (1 %–5 % and and 13 %–17 %) and finally in lake water (0.4 %–2 % and 5 %–7 %). Latin America has the highest SDFs for its continental scale freshwater ecosystem while the Northern regions exhibit the lowest SDFs. This is due to Latin America hosting the highest number of freshwater species, while the northern regions support the fewest.

Finally in the terrestrial ecosystem, for a specific region, unsurprisingly SDFs found for natural soil are higher than SDFs for agricultural soil, with 2 %–32 % and 60–90 % found at the continental and global scales respectively compared to 0.2 %–3 % and 5 %–8 % Same as the freshwater ecosystem, for the continental scale, Latin America has the highest SDFs and the Northern regions has the lowest. As seen previously, Latin America shows the greatest species diversity, in contrast to the northern regions, which have the least.

3.2.2.2. Polymer and size. CFs calculated with the species approach range between 5.74E-17 to 1.88E-05 PAF·day/kg$_{emitted}$ at the midpoint level. At the endpoint level, they vary between 1.57E-19 and 5.14E-08 PDF·year/kg$_{emitted}$.

As for the surface approach, Fig. 5 illustrates the intervals of endpoint CF values for the different polymers and sizes in the default region 'World'. The bars represent the range of values corresponding to the different emissions compartments.

In this approach, which accounts for the differences in species richness across the ecosystems, larger high-density polymers exhibit higher CFs than low-density polymers. This is due to the rapid settling of high-density particles. Although the EEF is higher in the water column, the higher SDF in sediment, combined with the smaller sediment volume relative to the water column, results in high overall CFs. Regarding the size of the polymers, similarly to the surface approach, larger particles size corresponds to higher CFs except for the high-density polymers with lower degradation rates in sediment (PLA, PAN).

3.2.2.3. Ecosystems and emission compartments. Fig. 6 illustrates the different CFs calculated in PDF·year/kg for all polymers, emission compartments and ecosystems for the minimum and maximum size.

Across all particle sizes and densities, the highest CFs for the species approach are often associated with the freshwater ecosystem (for emissions in the river water, lake water, air, natural and agricultural soil compartments). This can be easily explained for high-density particles: as shown in the surface approach, they settle quickly and therefore remain mainly in freshwater compartments when emitted in any compartment except marine ones. Furthermore, the volumes of lakes and rivers are smaller than the volume of the sea. Unlike the surface approach, which standardizes impacts over an equivalent area, the species approach accounts for the entire compartment. For the same emission into a given compartment, the impact is greater in a smaller compartment because the concentration of species exposed is higher.

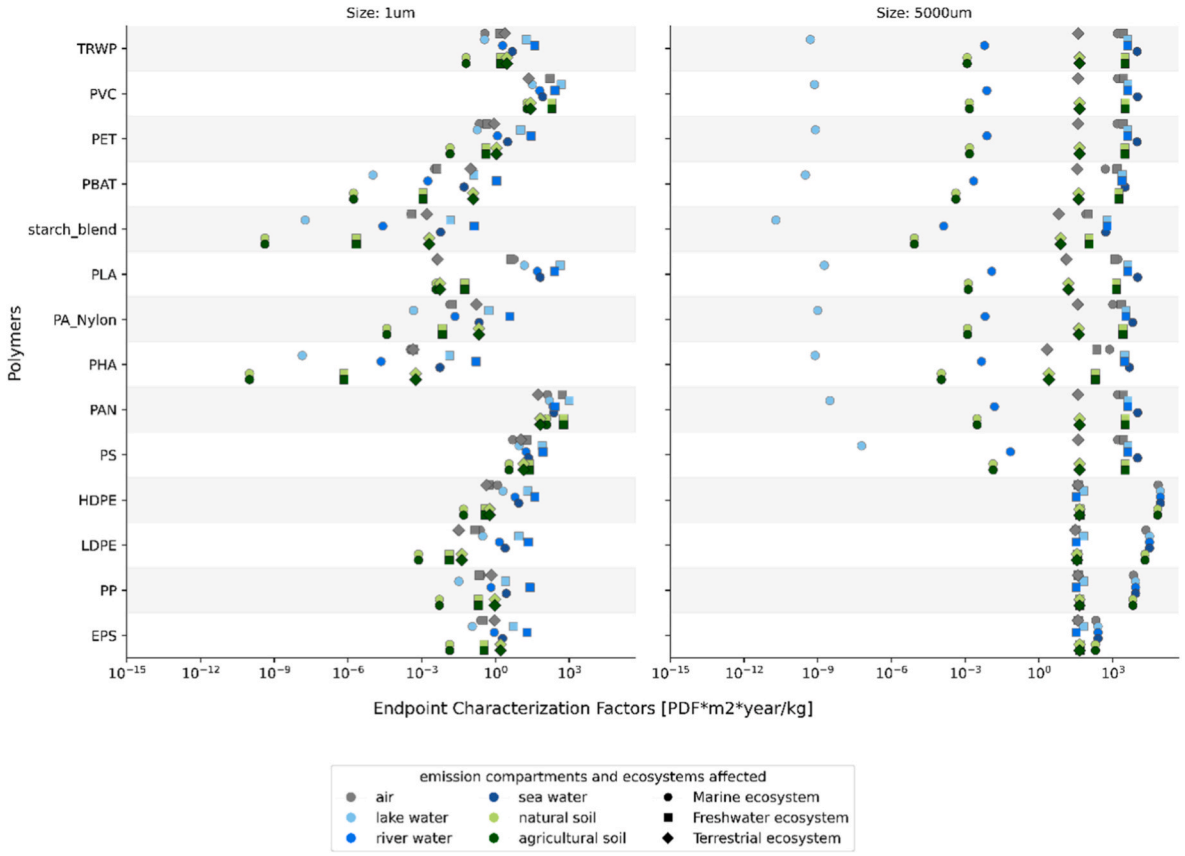

Fig. 4. Endpoint characterization factors (CFs) for physical effects on biota calculated in PDF·m^2·year/kg$_{emitted}$ shown for all polymers across the different environmental compartments at continental scale and for the different ecosystems. Emission compartments are indicated by colors and ecosystems affected are represented with distinct markers. The left graph illustrates endpoint CFs for the minimum particle size (1 μm), while the right graph represents the maximum particle size (5000 μm).

This also explains why we find higher CFs in freshwater, even for low-density particles that are expected to travel farther.

Regarding the impact on the marine ecosystem, the CFs of larger low-density polymers (100–5000 μm) are higher than those of smaller low-density polymers (1–100 μm), due to the longer residence time of larger particles in the marine environment. Conversely, as noted earlier, large high-density particles remain predominantly in freshwater environments compared to smaller ones and therefore have a reduced influence on the marine ecosystem unless they are directly emitted into it.

Finally, when looking at the impact on the terrestrial ecosystem, we observe that CFs are higher for emissions into natural soil than into agricultural soil, as natural soil has a higher SDF.

3.2.2.4. Regionalization interpretation. Endpoint CFs calculated in PDF·year/kg exhibit variations across the different regions for emissions in the same compartments (Fig. 7). These differences are mainly due to the variation in species distribution across regions as we have seen that only low variations occurred for the surface approach that does not consider the relative abundance of species in one region over another. Additionally, in both approaches, differences can be attributed to the varying volumes of different compartments. For instance, while Latin America, Southeast Asia, and Africa and the Middle East contain the highest species diversity in their freshwater compartments, the volume of Africa and Middle East's freshwater compartment is one order of magnitude smaller than the one of the other two regions. This difference leads to higher CFs for freshwater emissions in Africa and the Middle East compared to the rest of the world.

3.2.2.5. Sources and magnitude of CF variability. In the species approach, the CFs for different polymers, when considering the same size and emission compartments, vary up to 9 orders of magnitude for the smallest size and emissions in agricultural soil. Similar to the surface approach, the greatest CF variation across different sizes for a specific polymer is observed with PHA, spanning up to 11 orders of magnitude. For different emission compartments, CFs can vary by as much as 5 orders of magnitude for the same polymer and size. The highest variation is found for PLA at a size of 1 μm. Hence, in this approach, the size is also the source of the largest variability, followed by the polymer type (i.e. density and degradation rate) and the emission compartment.

3.3. Case study results

The results of the case study are presented in Fig. 8. For the impact category "physical effects on biota," scenario 1 (non-biodegradable mulch film) shows an impact of 15.55 PDF·m^2·year, while scenario 2 and scenario 3 (biodegradable mulch films) both exhibit a lower impact of 2.88 PDF·m^2·year. The values for scenarios 2 and 3 are identical because the same CF was applied, which is based on a starch blend polymer, with no distinction made based on the proportion of starch in the blend. The physical effects on biota account for 2.40 %, 0.34 %, and 0.43 % of the total impact on Ecosystem Quality (EQ) for scenarios 1, 2, and 3, respectively.

Scenario 2 is the least favorable option while both Scenario 1 with non-biodegradable mulch film and scenario 3 with a biodegradable mulch film made of 30 % of PBAT and 70 % of starch have an equivalent impact on EQ. We see that the composition of the biodegradable material is important as scenario 2 with a mulch film made of 70 % of PBAT and 70 % of starch has an impact 1.3 superior at scenario 3 which

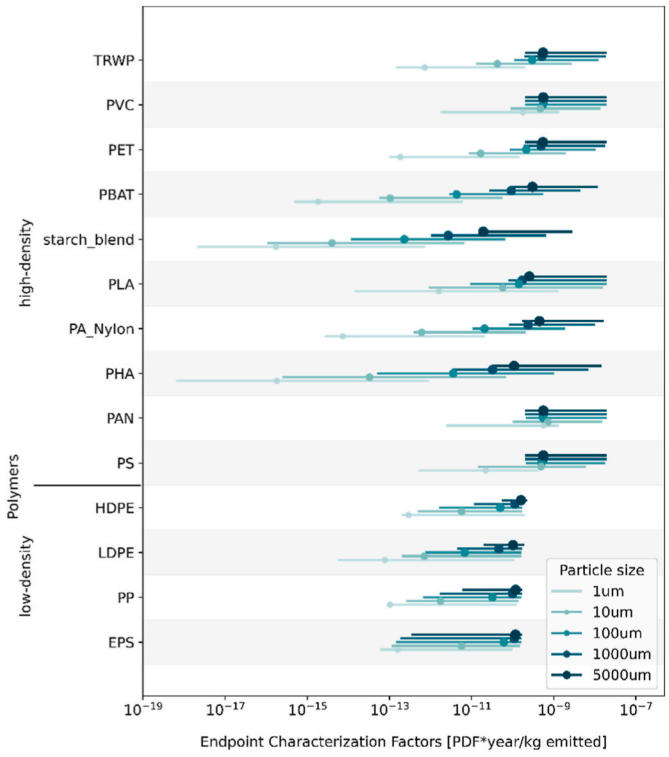

Fig. 5. Endpoint characterization factors (CFs) for physical effects on biota for emissions into air, lake water, river water, sea water, natural soil, agricultural soil at continental scale and for different polymers at different sizes calculated in PDF·year/$kg_{emitted}$. Bars represent the range of characterization factors for emissions in the different compartments and the point the median value of the CFs.

contains 30 % of PBAT and 70 % of starch.

The addition of microplastic impacts does not significantly affect the conclusions of this study. However, incorporating microplastic emissions in other studies could potentially influence their outcomes. This case study primarily involves emissions in soil, which exhibit lower CFs than emissions in freshwater or seawater for this particle size. Additionally, the particles emitted here range between 15 and 100 μm, while CFs for 1000 μm microplastic particles are typically 1 to 3 orders of magnitude higher. If we were considering an emission of 1000 μm LDPE and starch-blend particles here, the contribution of physical effects on biota would represent 40–97 % of the overall impact on EQ, highlighting the sensitivity of the results to the size of the emitted particles.

3.4. Comparison with other studies

Table 1 compares the CFs from this study with those of Corella-Puertas et al. (2023), Saadi et al. (2025) Schwarz et al. (2024), and Vázquez-Vázquez et al. (2025). For marine ecotoxicity, the presented CFs are 2 orders of magnitude higher than Corella-Puertas et al. and 1–3 orders higher than Schwarz et al., but similar to Saadi et al. This likely stems from the inclusion of sediment effects in our study and Saadi et al., which the others exclude. The same explanation may apply to freshwater ecotoxicity, where our CFs are 3–4 orders of magnitude higher than those of Schwarz et al., potentially due to faster sedimentation in shallower waters. For terrestrial ecotoxicity, our CFs exceed those of Vázquez-Vázquez et al. by 2 orders of magnitude. This can be due to the use of a terrestrial EF higher of also two orders of magnitude and differences in fate modeling and endpoint conversion.

3.5. Limitations and implications

3.5.1. Fate factors and fate model

This study develops a microplastic fate model based on SB4P and modified to align with USEtox which does not account for particulate pollutants (Rosenbaum et al., 2008). While it incorporates a range of physical mechanisms, simplified to ensure ease of implementation and adaptability, refinements could improve accuracy, particularly for sedimentation (e.g., biofouling effects) and particle shape (spherical assumption). Indeed, at this point the fate model is based solely on microbeads, although shape is known to influence transfer mechanisms and degradation rates (Chamas et al., 2020). Degradation is estimated via SSDRs, which represent the loss of material from the surface of plastic particles over time. SSDRs are calculated via experimental studies, however, the duration of these experiments is often too short to reliably extrapolate long-term microplastic degradation. Experts also emphasize the need to differentiate true biodegradation, which leads to mineralization, from polymer degradation, which may result in mass loss without necessarily achieving mineralization, yet still different from fragmentation. Currently, degradation measured indirectly (through surface loss, mass loss, or thickness reduction over short periods) is often misinterpreted as biodegradation data. As a result, characterization factors for non-biodegradable polymers may be underestimated due to an underestimation of their environmental persistence. To date, no enzymes have been identified that are capable of cleaving the covalent carbon–carbon bonds in high-molecular-weight polyolefins such as PE, PP, PS, and PVC (Chow et al., 2023). There is also insufficient data on degradation across all environmental compartments. Consequently, degradation rates measured in water are often applied to soil and sediment compartments, despite potential differences in degradation behavior.

Furthermore, the model does not include biotic-driven transport and does not differentiate between microplastics persisting in the global ocean or accumulating on distant coastlines. The "rest of the world" ocean compartment is treated as homogeneous, assuming all remaining species occupy all available volume in each ecosystem.

3.5.2. Exposure and effect factors

Three distinct EEFs are used for aquatic (Lavoie et al., 2022; Corella-Puertas et al., 2023), sedimentary (Saadi et al., 2025), and terrestrial organisms (Tunali and Nowack, 2025). However, due to limited ecotoxicological data, specific EEFs for marine and freshwater ecosystems have not been developed.

EEFs are derived from studies using various polymers and sizes, as data remains scarce. MP size and density likely influence effects and is related to the size of the species being exposed. Furthermore, current approaches do not separate exposure from actual impacts. Thus, it remains unclear whether EEF values are driven more by bioavailability (i.e. smaller particles would be bioavailable to more species) or the physical impact itself (a larger particle could cause more damage).

3.5.3. Characterization factors

The surface approach ensures that defined surface areas hosting species are weighted equally. As a result, protecting one square meter of an ecosystem—whether it be a lake, river, natural soil, agricultural soil, coastal zone, or ocean—is considered equally important, despite differences in species richness. This assumes that in less diverse ecosystems, each species plays a proportionally greater role in ecosystem functioning. Indeed, it has been shown that some species play a more critical role than others in maintaining a healthy, functioning ecosystem (Tilman et al., 1997; Estes et al., 2011). However, this approach may overrepresent local ecosystems that cover vast areas, such as oceanic ecosystems.

In the species approach, SDFs are used to account for the proportion of species present within a specific ecosystem compartment, assigning each species an equal weight within the global ecosystem (Marine,

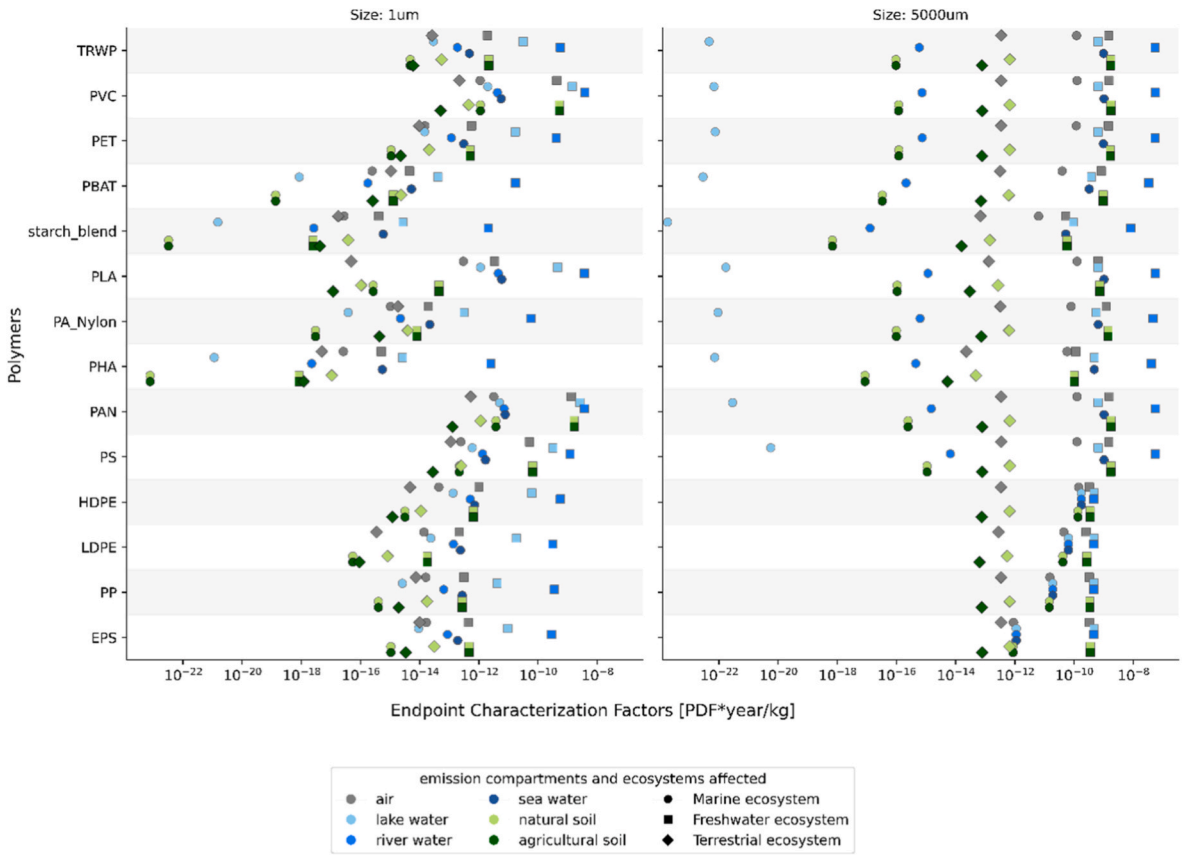

Fig. 6. Endpoint characterization factors (CFs) for physical effects on biota calculated in PDF·year/$kg_{emitted}$ shown for all polymers across the different environmental compartments at continental scale and for the different ecosystems. Emission compartments are indicated by colors and affected ecosystems are represented with distinct markers. The left graph illustrates endpoint CFs for the minimum particle size (1 μm), while the right graph represents the maximum particle size (5000 μm).

Freshwater, Terrestrial). This results in local ecosystems being weighted based on species diversity, assigning more importance to biodiverse regions (e.g., Amazon rainforest over boreal forest, coastal waters over open ocean) but downweighting unique, low-diversity environments like deserts.

Both methods offer complementary perspectives: one prioritizes ecosystem preservation based on area, while the other emphasizes species diversity at a global scale.

A global CF is computed with equal weighting for marine, freshwater, and terrestrial ecosystems, independent of species richness. This approach is chosen because each global ecosystem has unique intrinsic value and provides specific ecosystem services. This approach is also not dependent on our estimate of existing species which may be disbalanced due to lower knowledge of the ocean environment. If weighted by species diversity, terrestrial ecosystems would dominate, given the estimated 1,600,000 terrestrial, 250,000 marine, and 100,000 freshwater species (Goedkoop et al., 2013).

In this study, physical effect impacts are assessed at the ecosystem level (marine, freshwater, terrestrial) by aggregating impacts across multiple compartments. Sediment and water are ecologically inseparable within an ecosystem, though some species inhabit only one compartment. Effects are calculated at the compartment level for sediment and aquatic compartments but aggregated at the ecosystem level following Saadi et al. (2025), consistent with common LCA practice. We acknowledge, however, that this aggregation does not allow differentiation of impacts between sediment and water compartments when interpreting CFs for aquatic ecosystems.

Finally, it is important to note that no uncertainties were calculated for these CFs as such assessment was not possible at this time. Corella-Puertas et al. (2023) calculated uncertainties by propagating parameter uncertainties throughout their model and it resulted in a variation of ± 1 to 3 orders of magnitude around the CFs, mostly driven by sedimentation time and degradation time. While uncertainty on degradation rates and effect factor would be similar as previously assessed, due to the complexity of the fate model used, such assessment was not possible. The important variation due to the size of particle emitted and the polymer type however suggests that this is likely driving the uncertainty if unknown at the inventory level, and that working on improving polymer and compartment-specific degradation rates is important.

4. Conclusion and outlook

This work calculates regionalized CFs for two different approaches to assess the physical impacts of microplastic emissions on marine, freshwater, and terrestrial ecosystems. The assessment covers 14 different polymers, 5 sizes, 9 emission compartments, replicated across 2 scales, and 9 global regions, including 'World'. This is achieved by developing a regionalized fate model based on SimpleBox4Plastic (Quik et al., 2023) adapted to USEtox, integrating the combined effect and exposure factors from Lavoie et al. (2022), Saadi et al. (2025) and Tunali and Nowack (2025), while also implementing the Species Distribution Factors methodology established by Saadi et al. (2025).

The surface approach illustrates the proportion of ecosystem surface area degraded while the species approach gives information on the proportion of species lost from an ecosystem. Our findings indicate that the surface approach gives higher CFs for the marine ecosystem while the species approach gives higher CFs for the freshwater ecosystem which contains a large diversity of species for a small volume.

The results show that CFs are primarily influenced by particle size,

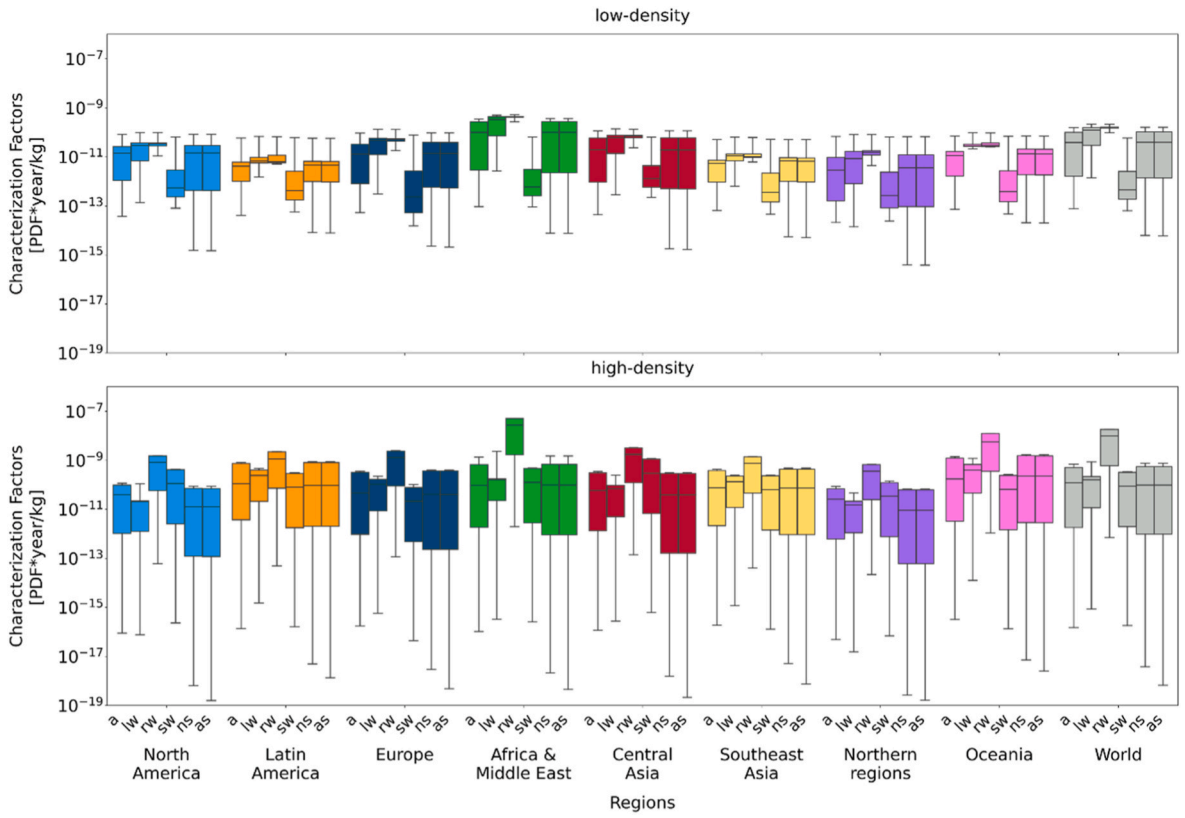

Fig. 7. Distribution of the endpoint characterization factors (CFs) calculated in PDF·year/$kg_{emitted}$ with added ecosystems for all polymers and sizes for the different regions and emission compartments at the continental scale with a: air, lw: lake water, rw: river water, sw: sea water, ns: natural soil, as: agricultural soil. The length of the box represents the difference between the 75th and the 25th percentiles, the bar in the middle is the median and the upper and lower whiskers are the minimum and maximum data values, excluding outliers.

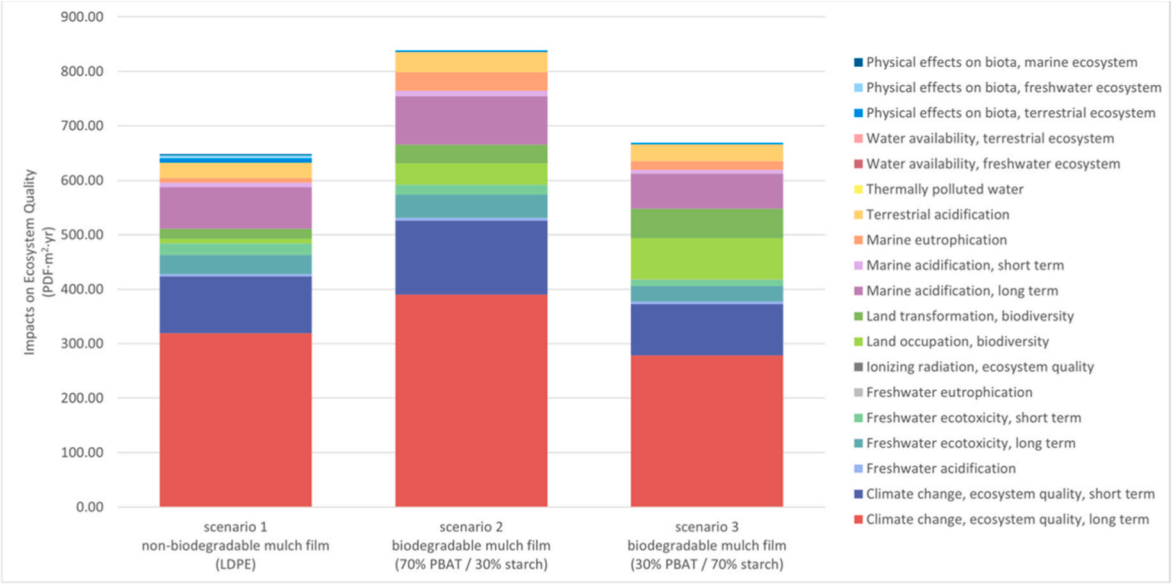

Fig. 8. Contributions of the different impact categories to Ecosystem Quality for the different mulch film scenarios studied to produce 1 ha of lettuce.

followed by polymer type and then emission compartment. Larger particles generally have higher impacts due to their longer lifetime in the environment. Regarding polymer types, biodegradable polymers degrade faster, reducing their environmental persistence and impact. Meanwhile, low-density polymers are more likely to be transported to marine environments, where they exert prolonged effects, whereas high-density polymers settle more quickly, primarily affecting sediment-dwelling species.

Ultimately, the two methods assess the environmental impact of microplastics differently, each offering its own advantages and limitations. They can be used complementarily to gain a more comprehensive understanding of microplastic impacts on ecosystems, depending on the

Table 1
Comparison of endpoint CFs on the physical impacts of microplastics on biota (in PDF·m^2·year or species·year per $kg_{emitted}$) of different studies for marine, freshwater and terrestrial ecotoxicity and LDPE and PP polymers. LDPE and PP particle sizes are 100 µm for this study, Corella-Puertas et al. (2023), Saadi et al. (2025), 272 and 72 µm respectively for Schwarz et al. (2024) and 50 and 450 µm for Vázquez-Vázquez et al. (2025).

	emission compartment	marine ecotoxicity			freshwater ecotoxicity			terrestrial ecotoxicity	
		This study (PDF·m^2·yr)	Corella-Puertas et al. (2023) (PDF·m^2·yr)	Saadi et al. (2025) (PDF·m^2·yr)	This study (species·yr)	Schwarz et al. (2024) (species·yr)	This study (species·yr)	Schwarz et al. (2024) (species·yr)	This study (PDF·m^2·yr)	Vázquez-Vázquez et al. (2025) (PDF·m^2·yr)
LDPE	marine water	4.77E+02	5.86E+00	7.05E+02	6.00E-07	6.04E-10	–	–	–	–
	freshwater river	4.75E+02	4.40E+00	5.29E+02	5.97E-07	5.97E-10	4.66E-05	9.89E-09	–	–
	freshwater lake	4.38E+02			5.40E-07		3.95E-05		–	
	soil nat	4.28E+01	–	–	4.77E-08	5.55E-10	1.79E-06	9.21E-09	3.80E+00	1.71E-02
	soil agr	4.28E+01			4.77E-08	5.16E-10	1.79E-06	8.56E-09	3.80E+00	
PP	marine water	1.64E+02	2.22E+00	1.35E+02	5.35E-07	1.30E-08	–	–	–	–
	freshwater river	1.60E+02	1.67E+00	1.01E+02	5.20E-07	1.30E-08	4.56E-05	1.00E-08	–	
	freshwater lake	1.13E+02			3.36E-07		2.14E-05		–	
	soil nat	6.99E+01	–	–	1.99E-07	1.29E-08	9.61E-06	9.94E-09	2.83E+01	3.43E-03
	soil agr	6.99E+01			1.99E-07	1.29E-08	9.61E-06	9.94E-09	2.83E+01	

objective: whether to preserve local ecosystems independently in terms of surface area or to protect species diversity on a global scale. Yet, both approaches fail to comprehensively address biodiversity issues and each focus on one angle only. More research is needed to develop LCIA models capturing biodiversity impacts more comprehensively. A possible opportunity for improvement could be the use of Global Extinction Probabilities (GEP), to scale the CFs based on the species probability of extinction (Verones et al., 2022).

The CFs are tested in a case study that demonstrates the importance of integrating the physical effects of microplastics on biota, even if in this case, the inclusions of microplastic emissions impacts do not change the conclusions of the study. More case studies should be conducted to really understand the influence of physical effects on biota of MP emissions in the total impact of plastic products on ecosystem quality.

Furthermore, this study limits the fate and the effect of microplastics to a spherical form, whereas, in reality, microplastics are emitted in various shapes, including cylinders and films. Further research is therefore needed to determine how particle shape influences fate, and adapt the model accordingly. The influence of microplastic shape on the physical effect on biota and its bioavailability must also be investigated.

Finally, this study provides a comprehensive assessment of the physical impact of microplastics across marine, freshwater, and terrestrial ecosystems simultaneously, using two different metrics for ecosystem quality damage assessment. The developed CFs can be directly integrated into existing LCA methods, with each approach providing CFs in a specific unit, ensuring better compatibility with different LCA methodologies.

CRediT authorship contribution statement

Juliette Louvet: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Joris T.K. Quik:** Writing – review & editing, Conceptualization. **Anne-Marie Boulay:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Funding acquisition, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

ChatGPT (GPT-4o-mini) was used to polish the English language for improved readability. The content was subsequently reviewed and edited by the authors as needed.

Funding sources

This work was funded by the Canada Research Chairs program.

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.

Acknowledgements

This research was undertaken, in part, thanks to funding from the Canada Research Chairs Program. The authors wish to thank Cécile Bulle for sharing her expertise on methodology for the surface approach. They also thank Nadim Saadi for his assistance with compartment aggregation and Carla Hajjar for her help with fate modeling.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2025.147217.

Data availability

The code used to generate the CFs for this study is openly accessible at the following address: https://github.com/Julouve/Regionalized_Characterization_Factors_for_Microplastic_Emissions_in_LCIA.

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