National Institute for Public Health
and the Environment
Ministry of Health, Welfare and Sport

Emission of Microplastics to Water, Soil, and Air

What can we do about it?

RIVM report 2024-0106
J.T.K. Quik et al.

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Colophon

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DOI 10.21945/RIVM-2024-0106

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This investigation was performed by order, and for the account, of the Ministry of Infrastructure and Water Management, within the framework of the Microplastics project

Published by:
National Institute for Public Health
and the Environment, RIVM
P.O. Box 1 | 3720 BA Bilthoven
The Netherlands
www.rivm.nl/en

Synopsis

Emission of Microplastics to Water, Soil, and Air

What can we do about it?

Microplastics enter the environment through products that contain plastics. The Ministry of Infrastructure and Water Management wants to know what the main sources of microplastics entering the environment are in the Netherlands. Based on this knowledge, the Ministry will be able to take measures to reduce these emissions.

This is an update of a previous study by RIVM on the emission of microplastics. RIVM has drawn up a more complete overview of the largest sources of emissions in the Netherlands. Most microplastics (80 percent) end up in the soil. Depending on the source, they can also be emitted into water or air. This has now been included in an updated model.

The three main sources of microplastics are tyre wear from road use, plastic pellets used by the industry to make plastic products, and plastic waste. Other sources of microplastics include paint, clothing, rubber granulate for synthetic turf fields and certain pesticides.

RIVM created an overview of measures that may be effective in reducing emissions. These measures have been discussed with experts. All measures can be useful. However, further assessment remains necessary whether these measures are feasible, are technically possible and will be supported by society and the industry.

Naturally, the greatest possible effect could be achieved by reducing the largest sources of emissions. For example, we could all cut back in use of plastic products. Moreover, additional regulations could prevent plastic pellets from leaking into the environment during transport or at industrial facilities. Finally, in order to reduce tyre wear, better tyres could be developed, and tyre wear particles could be filtered out by treating waste water from roads. Such treatment already takes place near cities, but not in more rural areas.

Keywords: microplastics, macroplastics, plastic, environment, emissions, measures, model, material flow analysis

Publiekssamenvatting

De uitstoot van microplastics naar water, bodem en lucht

Wat kunnen we eraan doen?

Microplastics komen in het milieu terecht via producten waar plastics in zitten. Het ministerie van Infrastructuur en Waterstaat (IenW) wil weten door welke bronnen de meeste microplastics in Nederland in het milieu terechtkomen. Op basis daarvan kan IenW maatregelen nemen om de uitstoot te verminderen.

Dit is een update van een eerder onderzoek van het RIVM naar de uitstoot van microplastics. Het RIVM heeft nu een completer overzicht van de uitstoot van grootste bronnen in Nederland gemaakt. De meeste microplastics (80 procent) komen in de bodem terecht. Afhankelijk van de bron kunnen ze ook in water en lucht terechtkomen. Ook dat is nu in kaart gebracht met een vernieuwd rekenmodel.

De drie grootste bronnen van microplastics zijn slijtage van banden op het wegdek, plastic korrels die de industrie gebruikt voor plastic producten, en plastic afval. Kleinere bronnen van microplastics zijn onder andere verf, kleding, rubber granulaat voor kunstgrasvelden en bepaalde pesticiden.

Het RIVM heeft maatregelen in kaart gebracht om de uitstoot te verminderen. Deze maatregelen zijn met experts besproken. Alle maatregelen kunnen nuttig zijn. Wel is er verder onderzoek nodig om te kijken of ze haalbaar zijn, technisch zijn uit te voeren en of er draagvlak voor is in de samenleving en de industrie.

Het grootste effect kan logischerwijs worden behaald door de uitstoot van de grootste bronnen te verminderen. Dat kunnen we door minder plastic te gebruiken. Verder zou extra regelgeving kunnen voorkomen dat de plastic korrels voor industrie weglekken tijdens transport of bij bedrijven. Tot slot kan bandenslijtage worden tegengegaan, bijvoorbeeld door betere banden te ontwikkelen. Verder kunnen deze slijtagedeeltjes worden opgevangen door afvoerwater bij wegen te zuiveren. Deze zuivering vindt al plaats rond steden maar niet rond wegen in gebieden daarbuiten.

Kernwoorden: microplastics, macroplastics, plastic, milieu, emissie, uitstoot, maatregelen, model, materiaalstroomanalyse

Contents

Summary

Introduction

Microplastics are formed through wear and tear of plastic products, such as tyre wear, or sanding of paint. They can also be produced intentionally, for instance as infill for artificial sports fields, or are formed in the environment due to fragmentation of macroplastics. Microplastic pollution is a potential hazard to human health and ecosystems; it is a material loss factor in the circular economy, and lowers the intrinsic value of our environment.

RIVM developed a harmonized and open access model, that uses a material flow approach, to calculate microplastic emissions into the environment from various sources. Next, an inventory of mitigation measures was made from literature and an expert workshop. The model was then also used to calculate a first reduction potential of a selection of measures.

Model approach

A material flow analysis approach is used to estimate the flow of twelve common plastic polymers and tyre rubber within the technosphere and their release into the environment. This research combines data from various sources in order to compare sources and mitigation measures. This covers seven major sources of microplastics:

1. Pre-production pellets;
2. Tyres;
3. Paints and coatings;
4. Textiles;
5. Agriculture;
6. Intentionally produced polymer microparticles;
7. Macroplastics and packaging.

In order to inform the effectiveness of mitigation measures, we have selected 23 mitigation measures for further analysis on the basis of the combined insight from literature and experts. The selection included measures covering various aspects of a circular economy: narrowing, slowing and closing the loop. The reduction in emissions of micro- and macroplastics to the environment by 2030 and 2050 was calculated using a generic level of 30% efficiency and feasibility for each measure in order to compare the reduction potential across all 7 sources. This is thus not an absolute estimate of the reduction potential, but only useful for a first ranking of measures. The reduction potential is dependent on where in the life cycle or value chain the measure (intervention) is placed, how close to the source of emission it is, and the size of emission per source.

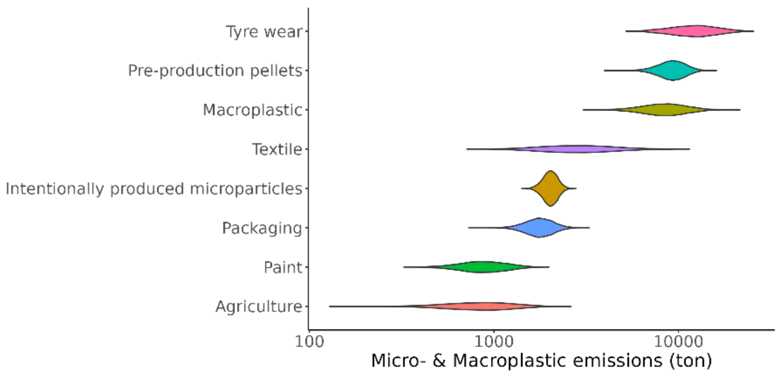
Emission estimates

The largest three sources of plastics in the environment are:

1. Tyre wear due to abrasion of tyres;

2. Pre-production pellets due to losses at industrial plants and during transport;
3. Macroplastics ending up in the environment due to mismanaged waste.

An overview of emission from all sources is provided in the figure below.



Effect of mitigation measures

The top ten mitigation measures ranked from most to least reduction potential in plastic emissions are:

- Restricting microplastic consumption (for instance by reducing single-use plastics, or by using alternative materials);
- Increasing treatment of tyre wear in road runoff, specifically outside of urban areas;
- Reducing tyre wear (for instance by innovative tyre design or lowering mileage);
- Cleaning up macroplastics in the environment;
- Reducing pellet loss at industrial plants;
- Reducing plastic polymer use in technical textiles;
- Improved maintenance of technical textiles in order to reduce in use releases;
- Improved road cleaning to capture tyre wear;
- Preventing spillage of pellets during transport;
- Reducing polymer-based material use in agriculture, for instance by using more biodegradable plastics.

As expected, the highest-ranking mitigation measures are aimed at the largest sources. For some sources, such as pre-production pellets, new regulations have already been prepared at the European level to limit spillage to the environment. For other sources, it is expected that further product-specific and other regulations will be developed to include mitigation of micro- and microplastic releases to the environment. This presented ranking should be used to further assess the absolute effect of measures prioritized by policy makers. This is important follow-up research as it may result in a new, updated, order of ranking that combines the effectiveness of measures with the feasibility in practice. This presented ranking should be used to further assess the absolute effect of measures prioritized by policy makers. This is important follow-up research as it may result in a new, updated, order of ranking that combines the effectiveness of measures with the feasibility of the measures in practice.

Conclusions

Most effective are measures aimed at reducing microplastic emissions from macroplastics, tyre wear and pre-production pellets. A whole range of measures aimed at narrowing and closing the loop can be effective, but require different implementations at various spatial, geographical and economical scales. This should be part of further research, which should be aimed at deriving the level of efficiency and feasibility for implementation for each mitigation measure.

Tyre wear, pre-production pellets and macroplastics are the largest sources of plastics ending up in the environment. The modelling approach applied here has provided a broad overview considering seven major sources of microplastics and the effect mitigation measures have on reducing the emissions in the Netherlands and Europe. The applied model is flexible in its application and can support various types of studies, for instance on the transition towards a (more) circular application of plastics, or supporting risk assessment of microplastics. This is relevant to policymakers working on the reduction of plastic pollution.

Samenvatting

Inleiding

Microplastics worden gevormd door slijtage van plastic producten, bijvoorbeeld bandenslijtage of het schuren van verf. Ze kunnen ook opzettelijk worden geproduceerd, bijvoorbeeld als rubber granulaat voor kunstgrasvelden, of in het milieu worden gevormd door fragmentatie van macroplastics. Vervuiling door microplastics is een potentieel gevaar voor de gezondheid van de mens en milieu. Het is materiaalverlies in een circulaire economie en verlaagt de intrinsieke waarde van onze leefomgeving.

Het RIVM heeft een geharmoniseerd en open access model ontwikkeld voor het doen van een materiaal stroomanalyses van plastics emissie naar het milieu vanuit verschillende bronnen. Vervolgens zijn maatregelen geïnventariseerd op basis van literatuur en een expert workshop. Het model is gebruikt om voor een selectie van maatregelen een eerste schatting van het emissie reductie potentieel uit te rekenen.

In dit rapport geven we een overzicht van de uitstoot van microplastics naar bodem, water en lucht vanuit belangrijke bronnen. Hiervoor gebruiken we een geharmoniseerd model. Vervolgens wordt de effectiviteit van maatregelen gericht op het verminderen van microplasticvervuiling beoordeeld om deze te helpen prioriteren voor beleidsontwikkeling in Nederland.

Modelaanpak

Met een materiaalstroomanalyse wordt voor twaalf veelvoorkomende plastic polymeren en bandenrubber geschat in welke mate ze vrijkomen in het milieu. Dit onderzoek combineert verschillende gegevens om diverse bronnen van microplastics en maatregelen tegen emissies met elkaar te vergelijken. Dit omvat zeven belangrijke bronnen van microplastics:

1. Kunststofpellets;
2. Banden
3. Verf en coatings;
4. Textiel;
5. Landbouw;
6. Synthetische polymeermicrodeeltjes;
7. Macroplastics en verpakkingen.

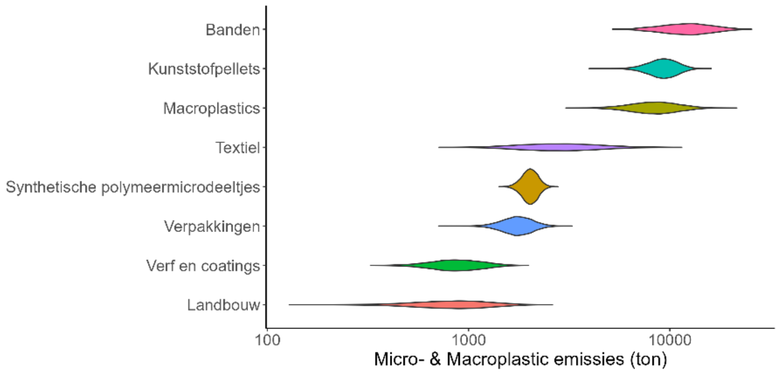
Om de effectiviteit van maatregelen tegen microplastics vervuiling in te schatten hebben we 23 maatregelen geselecteerd voor verdere analyse. Dit is gedaan op basis van gecombineerde inzichten uit literatuur en van experts. De selectie omvatte maatregelen die betrekking hadden op verschillende aspecten van een circulaire economie: het verkleinen, vertragen en sluiten van de kringloop. De vermindering van de uitstoot van micro- en macroplastics in het milieu in 2030 en 2050 werd berekend op basis een generiek niveau van 30% efficiëntie en haalbaarheid voor elke maatregel om zo de potentiële emissie reductie van de maatregelen over de 7 bronnen heen te vergelijken. Dit is dus geen absolute inschatting van het reductiepotentieel, maar enkel nuttig voor een eerste rangschikking van maatregelen.

Emissieschattingen

De drie grootste bronnen van kunststoffen in het milieu zijn:

1. Bandenslijtage;
2. Verliezen van kunststofpellets bij industriële installaties en transport;
3. Macroplastics, die vooral in het milieu terechtkomen door slecht beheer van afval.

Het overzicht van de emissie uit alle bronnen is weergegeven in de onderstaande figuur.



Effect van maatregelen

De top tien van mitigerende maatregelen, gerangschikt van de grootste naar de geringste vermindering van de plasticuitstoot, zijn:

- Beperk het gebruik van macroplastics (bijvoorbeeld door het gebruik van alternatieve materialen of door plastic voor eenmalig gebruik te verminderen);
- Uitgebreidere zuivering van bandenslijtagedeeltjes uit afvalwater van wegen, met name buiten stedelijke gebieden;
- Minder bandenslijtage (bijvoorbeeld door innovatief bandenontwerp of lagere kilometrage);
- Macroplastics in het milieu opruimen;
- Verminder het verlies van kunststofpellets uit industriële installaties;
- Verminder het gebruik van plastic polymeren in technische toepassingen van textiel;
- Verbetering van het onderhoud van technisch textiel om het vrijkomen van microplastics tijdens het gebruik te verminderen;
- Toename in wegreiniging om bandenslijtage op te ruimen
- Voorkom morsen van pellets tijdens transport;
- Verminder het gebruik van materialen op basis van polymeren in de landbouw, bijvoorbeeld door meer biologisch afbreekbare kunststoffen te gebruiken.

Zoals verwacht zijn de meest effectieve maatregelen gericht op de grootste bronnen. Voor sommige bronnen, zoals pre-productie pellets, zijn op Europees niveau al nieuwe voorschriften opgesteld om het morsen in het milieu te beperken. Voor andere bronnen wordt verwacht dat product specifieke en andere regelgeving verder worden ontwikkeld om vervuiling door micropalstics tegen te gaan. Deze ranglijst van maatregelen moet worden gebruikt voor verder onderzoek naar het absolute effect van maatregelen die door beleidsmakers worden geprioriteerd. Dit is belangrijk vervolg onderzoek dat mogelijk leidt tot een nieuwe, updatet ranglijst welke de effectiviteit combineert met de haalbaarheid in praktijk.

Conclusies

Het meeste effect hebben maatregelen gericht op verminderen van microplastics emissies van macroplastics, banden slijtage en pellets. Verschillende soorten maatregelen gericht op het verkleinen en het sluiten van de kringloop kan effectief zijn, maar vereisen ze toepassing op verschillende ruimtelijke, geografische en economische schalen. Verder onderzoek moet de maatregelen verfijnen, bijvoorbeeld door een gekwantificeerd niveau van efficiëntie en haalbaarheid per toe te passen maatregel af te leiden.

Banden slijtage, pellets en macroplastics zijn de grootste bronnen van microplastics in het milieu. De hier toegepaste modelleringsaanpak gaf een breed overzicht van de zeven belangrijkste bronnen van microplastics en het effect van mitigerende maatregelen op het terugdringen van de uitstoot in Nederland. De modelaanpak is flexibel in zijn toepassing en kan verschillende soorten studies ondersteunen, zoals studies naar de transitie naar een (meer) circulaire toepassing van kunststoffen of ter ondersteuning van risicobeoordeling van microplastics. Dit is relevant voor beleidsmakers die werken aan het verminderen van vervuiling door kunststoffen.

1 Introduction

The Dutch Ministry of Infrastructure and Water Management (I&W) wants to further develop policies that contribute to reducing microplastic pollution of the environment. This is in line with the European Circular Action Plan and Plastic Strategy, in which microplastics is one of the priorities for which goals are being set to minimise and mitigate emissions to the environment (EC, 2020).

The emission of microplastics should be avoided on the basis of various perspectives on microplastic emission (Waaijers-van der Loop et al., 2022). For instance:

1. The emission of microplastics can create a hazard for human health and ecosystems in the long term (risk-based perspective), as described in literature on microplastics (for example (Coffin and Weisberg, 2022; Koelmans et al., 2022)) (Figure 1); or
2. The emission of microplastics should be avoided at all reasonable costs because it violates the intrinsic values of our environment (the zero-pollution-based perspective)(European Commission, 2021);
3. The emission of microplastics is considered as a material loss in a circular economy.[1]

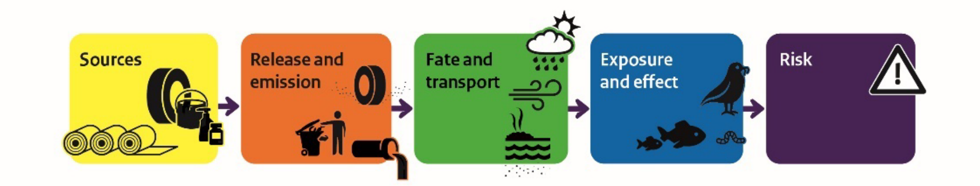


Figure 1 Plastic use leads to release and emission of microplastics. Through fate and transport processes organisms are exposed. An exposure above the risk limit leads to adverse effects.

The optimal mitigation measures and policy actions to deal with microplastic emissions may vary, depending on the perspective. For example, the risk-based perspective may seek to limit or prevent the emission of microplastics on the basis of hazard-based thresholds, while the circular economy perspective may seek to not only limit emission but also collect material so it can be re-used. In this report, we provide a uniform overview of the emission of microplastics to soil, water and air in order to assess the effectiveness of mitigation measures aimed at reducing microplastic pollution and help prioritise Dutch policy development.

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[1] I&W (2018) 'Kamerbrief, betreft Gezamenlijke aanpak plastic zwerfafval' Reference IENW/BSK-2018/232541 (Parliamentary Paper concerning Joint approach to tackling plastic litter) dated 6 November 2018, The Hague

While several studies on estimating microplastic emissions are available, this study is tailored to the needs of Dutch policymakers by including the following aspects:

- Estimates for the Netherlands;
- Group microplastics sources based on the remit of existing regulatory frameworks, for instance for pre-production pellets and intentional microplastics;
- Including paint and six other sources of micro- and macroplastics;
- Including emissions to soil and air;
- Including temporal dynamics in estimating the effectiveness of mitigation options

Most of these aspects have already been considered separately in other studies, but not combined into a comprehensive analysis. Such a comprehensive analysis does entail relatively large uncertainties due to the lack of data for certain processes. However, the model and its application framework are made available for future re-use, which should result in refinements being included in future analysis. Nevertheless, the estimates here clearly show the magnitude of microplastic emissions to the environment and the most promising mitigation measures to focus on.

1.1 Objectives and scope

The aim of this report is twofold. The first aim is to estimate the magnitude of the emission of major microplastic sources to water, soil and air. This can be seen as a follow-up to previous RIVM work, estimating emissions for several sources, such as paint and textiles (Verschoor et al., 2016, 2014; Verschoor and De Valk, 2018). The second aim is to rank the potential of mitigation measures to reduce microplastic emissions to the environment for the major microplastic sources. These estimations are aimed at supporting the Dutch government to develop policies that contribute to reducing plastic pollution in the environment. Even though the Ministry of Infrastructure and Water Management commissioned this report, the policy theme of microplastics is cross-cutting and also concerns the Ministries of Public Health, Welfare and Sport (VWS), Agriculture, Nature and Food Quality (LNV), and Economic Affairs and Climate (EZK).

Consequently, the following scope is considered:

- The study is aimed at the Netherlands, but in less detail also assesses emissions on the European scale for comparison. Furthermore, some measures are implemented more effectively at European level, while some are more effective at national level.
- Following EU and Dutch assessments of major sources (EC, 2023a; Urbanus et al., 2022; Verschoor and de Valk, 2018), seven microplastics sources are considered:
    1. Pre-production pellets;
    2. Tyres;
    3. Paints and coatings;
    4. Textiles;
    5. Agriculture;

6. Intentionally produced polymer microparticles;
7. Macroplastics.

- On the basis of the available data, fourteen categories of polymers are identified:
  1. Polypropylene (PP);
  2. Low-density polyethylene (LDPE);
  3. High-density polyethylene (HDPE);
  4. Polyvinylchloride (PVC);
  5. Polyamide (PA);
  6. Polyethylene terephthalate (PET);
  7. Polyurethane (PUR);
  8. Polycarbonate (PC);
  9. Polystyrene (PS);
  10. Expanded Polystyrene (EPS);
  11. Acrylonitrile butadiene styrene (ABS);
  12. Poly(methyl methacrylate) (PMMA);
  13. Tyre rubber: consists of Styrene Butadiene Rubber (SBR) and Natural Rubber (NR);
  14. Other polymers as a group of non-specified polymers.
- The same modelling framework was applied to all sources in order to compare outcomes.
- Uncertainty associated with the model input data and parameters was included, because the uncertainty of emissions is considered to be large (EC, 2023a).
- For the estimation of the emission volumes, 2019 was taken as the reference year, similar to the recent EU studies (EC, 2023a, 2023b). Historical and future projections are applied for estimating the effect of mitigation measures for the years 2030 and 2050 on the basis of the OECD plastics outlook (OECD, 2022).
- About three mitigation options per source were taken into account using a uniform level of feasibility and technical effect.

The current study has several limitations with regard to the scope and data sources being applied. Most details are presented in the Methods section and appendices, but key limitations are:

- Several data sources are not specific to the Dutch situation, for instance the contamination levels of compost or plastic consumption in agriculture; this is accounted for by increasing the uncertainty and, when needed, the application of scaling factors. Given that reporting on microplastic releases is part of the sustainability reporting standards (EC, 2023c), this might change in the future.
- The emission reduction of mitigation measures is not calculated based on realistic estimates of efficiency or feasibility of measures. The potential for mitigation reduction is compared between each measure based on the relative contribute of a 30% efficiency/feasibility compared to the total environmental emission of plastics. This is a first step and needs follow up research.
- To assess mitigation measures, changes through time of material flows and existence of legacy applications dating back to 1950 are accounted for in a simplified approach; this specifically

impacts sources for which products have a long lifetime, such as technical textiles.
- The fate of microplastics in environmental compartments is not accounted for. For instance, the emission to water is given, but deposition of microplastics from water to sediment or transport downstream is not considered here. This is necessary when comparing results to environmental monitoring measurements.
- In some cases, no input data was available for the Netherlands (i.e. plastic consumption in agriculture), so EU data was scaled to the Netherlands using scaling factors.

1.2 Sources of microplastic emissions and their main sources

Table 1 Estimated releases from the six sources of unintentional microplastics release to the EU environment.

Source	Quantity (tonnes/year), 2019
Paints	231 000 – 863 000 (average 482 000)
Tyres	360 000 – 540 000 (average 450 000)
Pellets	52 140 – 184 290
Textiles	1649 – 61 078
Geotextiles	6000 – 19 750
Detergent capsules	4140 – 5980
TOTAL of the selected six sources	654 929 – 1 674 098 (90-93% of total emissions)
TOTAL of all sources	729 087 – 1 808 198

Source: (EC, 2023a)

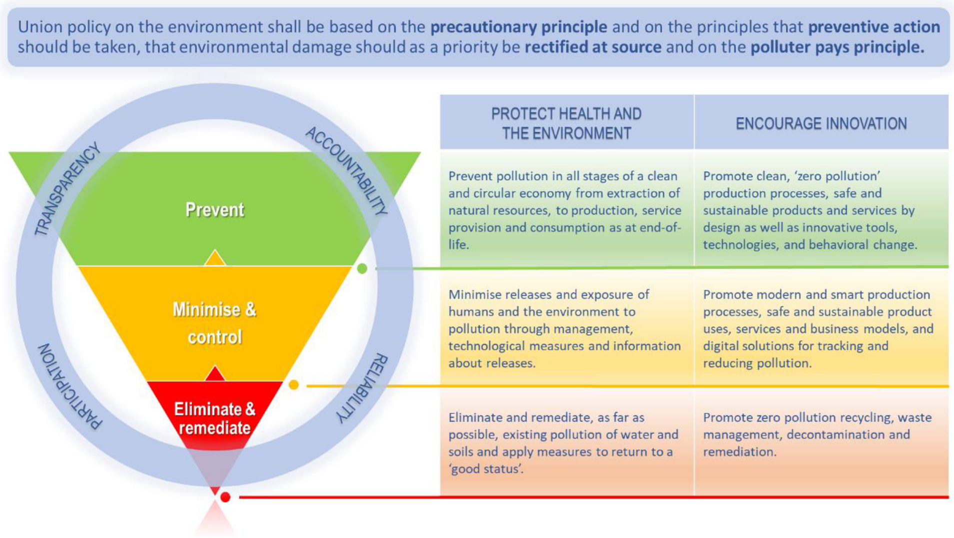
In a recent study that accompanied the proposal for regulating the emission of so-called pre-production pellets, six major sources of unintentional releases of microplastics were identified (EC, 2023b), see Table 1. Another important source is the already regulated intentionally produced microplastics, the so-called intentionally produced polymer microparticles or synthetic polymer microparticles (EC, 2023d). On the basis of further literature research, packaging and agriculture were included in this study for further analysis (OSPAR Commission, 2017; Rutgers et al., 2022; Vercauteren et al., 2021). Eventually, due to lack of data, detergent capsules were not quantified further. Geotextiles were included in a broader group of technical textiles, which also include other technical textile applications such as in construction and agriculture.

Macroplastics is a very broad category, which includes various kinds of plastic products that end up in the environment. An important part of this category is plastic packaging that ends up as litter in the environment. However, macroplastics also come from mismanaged waste from applications in construction and agriculture, for instance geotextiles or mulching films.
Several estimates for the Netherlands are already available for these plastic sources (Hoeke et al., 2024; Urbanus et al., 2022; Verschoor and de Valk, 2018). The study by Verschoor and de Valk (2018) reports data

on microplastic emissions to water for 2015, based on a methodology developed for the OSPAR (OSPAR Commission, 2017). The first goal of this report was aimed at updating and extending the work done by Verschoor and de Valk (2018). The study by Urbanus et al. (2022) partly contributed to extending the insight into emissions of microplastics in the Netherlands to other sectors and including emissions going to soil. A recent study by Hoeke et al. (2024) reported on emissions from tyre wear and rubber granule application in artificial turf pitches. In Chapter 3, the emission estimates presented here will be further discussed in relation to these previous studies.

1.3 Mitigation of microplastic emissions

Quantifying the emissions of microplastics from various sources is the starting point for prioritising mitigation measures. Mitigation measures can be divided into three categories following the zero-pollution hierarchy: (i) prevent, (ii) minimise & control and (iii) eliminate & remediate (Figure 2) (European Commission, 2021).



Union policy on the environment shall be based on the **precautionary principle** and on the principles that **preventive action** should be taken, that environmental damage should as a priority be **rectified at source** and on the **polluter pays principle.**

PROTECT HEALTH AND THE ENVIRONMENT	ENCOURAGE INNOVATION
Prevent pollution in all stages of a clean and circular economy from extraction of natural resources, to production, service provision and consumption as at end-of-life.	Promote clean, ‘zero pollution’ production processes, safe and sustainable products and services by design as well as innovative tools, technologies, and behavioral change.
Minimise releases and exposure of humans and the environment to pollution through management, technological measures and information about releases.	Promote modern and smart production processes, safe and sustainable product uses, services and business models, and digital solutions for tracking and reducing pollution.
Eliminate and remediate, as far as possible, existing pollution of water and soils and apply measures to return to a ‘good status’.	Promote zero pollution recycling, waste management, decontamination and remediation.

Figure 2 The zero-pollution hierarchy – reversing the pyramid of action, prioritising the approaches for tackling pollution.
Source: (European Commission, 2021)

Prevention measures are preferred, as they cause less waste to be generated. Prevention measures are often aimed at redesign (i.e. using less plastic in products or using biodegradable polymers), and at mitigation of use and consumption (de Smet et al., 2019). Minimise & control measures preventing microplastics from entering the environment, while eliminate & remediate measures are geared toward cleaning up microplastics already present in the environment (European Commission, 2021).

The mitigation measures for each source were selected on the basis of both information from literature and practice. The practical information was gathered during a workshop with stakeholders who are all experts on microplastics for the Dutch and European context and for different sources of microplastics. These are experts from universities, NGO’s, knowledge institutions, consultancies and governmental organizations. This was done in line with the Solution-focussed approach (Zijp et al., 2016) to further identify measures where literature sources were lacking (Table 2) and to discuss and score their effectiveness and feasibility. Approximately three measures were selected per source (see paragraph 2.4.2). Using the model, the effectiveness of the mitigation measures is estimated and compared.

Table 2 Overview of microplastic sources and known mitigation measures with examples of literature sources.

Source microplastics	**What is known about mitigation measures**
Tyres	Measures identified in literature (Gehrke et al., 2023; Hoeke et al., 2024; OECD, 2021)
Textiles	Measures identified in literature (Verschoor et al., 2014; Zwart and Valk, 2019)
Paint	Measures identified in literature (Faber et al., 2021; Verschoor et al., 2016; Verschoor and de Valk, 2018)
Pre-production pellets	Measures identified in literature (EC, 2023e; Faber et al., 2023)
Agricultural plastics	More measures to be identified, more knowledge needed (Bertling et al., 2021; Hofmann et al., 2023)
Soap capsules	More knowledge needed (EC, 2023f)
Macroplastics (incl. packaging)	More measures to be identified, including recycling facilities (Vercauteren et al., 2021)
Geotextiles	More measures to be identified, more knowledge needed (de Visser et al., 2022; Gustavsson et al., 2022)

2 Methods and Modelling approach

2.1 Classification of microplastics

Plastics can be made up of various types of polymers (such as polypropene, polyethylene, polystyrene, and polyvinylchloride) together with other additives; these are chemical properties. On the basis of their size, plastics emitted to the environment, can be divided into macro-, meso-, micro-, and nanoplastics. Over the last decade, several slightly differing definitions for microplastics have been proposed (Verschoor, 2015). In this report, we include size in distinguishing between microplastics (<5 mm) and macroplastics (> 5mm). This is in line with the recent definition used in the context of the proposed restriction on intentionally produce polymer microplastics, which is considered to be most relevant and is further described below.

In its opinion on the restriction, the European Chemicals Agency (ECHA) Risk Assessment Committee (RAC) defined microplastics as ‘particles containing solid polymer to which additives or other substances may have been added, and in which ≥ 1% w/w of particles have (i) all dimensions ≤ 5 mm, or (ii) a length of ≤ 15 mm and a length to diameter ratio of >3’ (ECHA, 2020a). The definition does not discriminate between the type of polymer used and sets no lower size limit. While the upper size limit for microplastics is widely accepted, the lower size limit is still under debate. This is also the case for the definition proposed in the restriction; ECHA initially proposed 100 nm as the lower size limit, while RAC recommended setting no lower size limit, and the sister committee for Socio-economic Analysis (SEAC) recommended defining a lower size limit of 1 nm and a temporary limit of 100 nm in order to ensure the enforceability of the restriction (ECHA, 2020b). In this study, we consider emissions of various polymer types and do not consider a lower size limit and report microplastic emissions in mass.

2.2 Introducing the Material Flow Analysis (MFA)

In this study, we used a material flow analysis (MFA) model to calculate the flow of plastic polymers within the technosphere and their release into the natural environment. Material flow analysis models are commonly used to assess and predict the flow of materials within a system (see Box 1). In the MFA conducted here, we include the uncertainty and variability of flows throughout the system in a probabilistic approach: Probabilistic MFA (see Box 2). However, to properly investigate mitigation measures, the temporal dynamics of the system were also taken into account, applying a so-called dynamic probabilistic MFA (DPMFA) (Kawecki et al., 2021a). The dynamic aspect of the model allows for the accumulation of materials in use over time and the delayed release of these materials (see Box 3).

Previous research has demonstrated the efficiency of MFA models (probabilistic and/or dynamic) in evaluating plastic production, consumption, waste generation, and emissions at different spatial scales: national (D. Kawecki and Nowack, 2019; Urbanus et al., 2022), EU (Kawecki et al., 2021a, 2018) and global (Schwarz et al., 2023). The MFA in this study is based on the dynamic probabilistic material flow analysis (DPMFA) model developed by Kawecki et al. (2021a). The model structure was adjusted to include ‘in-use’ emissions to environmental compartments (such as soil, water, and air). This was achieved by introducing conceptual compartments for ‘in-use’ and ‘discarded’ phases for plastic product categories with lifetimes for these stock compartments. This was done to differentiate emissions occurring during product usage (in-use emissions) from those relating to product disposal (end-of-life emissions). For instance, the emission of microplastics from clothing during their wear and use is assessed independently from the streams associated with textile waste generation. Additional modifications are based on including transfer coefficients from various available MFA models in order to consider two spatial scales (EU and the Netherlands) and thirteen polymers for a selection of microplastic sources. The available MFA models are from the following sources: (Hoeke et al., 2024; Kawecki et al., 2018; D. Kawecki and Nowack, 2019; Liu and Nowack, 2022; Schwarz et al., 2023; Sieber et al., 2020; Urbanus et al., 2022; Verschoor et al., 2016).

An MFA uses two types of input data (Figure 4, Box 1):

- External inflow data on polymer use or consumption for a specific source at Dutch or EU scale
- Transfer coefficient data describing the material flows through the system (i.e. transfer coefficients representing various mechanisms, for example the fraction of produced fibres that is used for clothing versus carpets, the fraction of wall paint that weathers during its lifetime, the fraction of produced compost that is applied on residential soil versus agricultural soil, or the fraction of mixed waste that is recycled versus incinerated).

Table 3 Input of produced, imported and consumed polymer products linked to the reported categorisation of sources of microplastics and macroplastics.

Input of polymers	**Categorisation of sources**
Domestic production and import of virgin pre-production pellets	Pre-production pellets
Tyre wear	Tyre wear
Paints and coatings	Paints and coatings
Textiles: clothing, household, and technical textiles	Macroplastics Textiles (microplastics) Recycling to pre-production pellets
Agriculture	Macroplastics Agriculture (microplastics) Recycling to pre-production pellets
Intentionally produced polymer microparticles (primary microplastics)	Intentionally produced polymer microparticles

Input of polymers	Categorisation of sources
Packaging	Macroplastics Packaging (microplastics) Recycling to pre-production pellets

This MFA considers seven major sources (inflows) of polymers that result in emission of macro- and microplastics (Figure 3). These seven inflows of polymer applications are categorised into seven sources, on the basis of their fit to policy and regulatory domains, i.e. as part of the ECHA restriction on intentionally produced polymer microparticles (primary microplastics) (EC, 2023d; ECHA, 2020b) and the identified sources of unintentionally released microplastics (secondary microplastics) (BIOIS, 2022; EC, 2023a), see also Section 1.2 and Table 3. The modelling accounts for overlap in these categories, i.e. the agricultural use of primary microplastics is not included in the general agricultural category, but is part of the primary microplastics category instead. Furthermore, the model separates the production and application of pre-production pellets in the Netherlands and the EU from the various product categories in which these pellets are eventually used for manufacturing purposes. This was done for two reasons: First, product-specific data on import and domestic production in the Netherlands and the EU is not readily available, and second, pre-production pellet losses is identified as a separate category of interest on the basis of the EU proposal to regulate this source (EC, 2023e), irrespective of the product categories these raw materials are applied in. For these reasons, the production losses considered are all related to pellet losses, while other losses in manufacturing are not considered, see Figure 3.

First, this MFA model is used to predict the overall emission of macro- and microplastics to the environment for 2019 as the reference year. The result is the total amount of plastics that enter the environment either as micro- or macroplastics. Second, the MFA model is used to estimate the theoretical effectiveness of various mitigation measures for prioritisation. This is done by comparing the environmental emissions in 2030 and 2050 for various mitigation measures to the baseline scenario where the future plastics consumption follows the OECD global plastics outlook scenario. The mitigation measures have been identified by means of a participatory workshop and literature. Further details on the mitigation measures that have been identified and the modelling approaches that were followed can be found below and in the appendices. The model code and input data is available from https://doi.org/10.5281/zenodo.12636554.

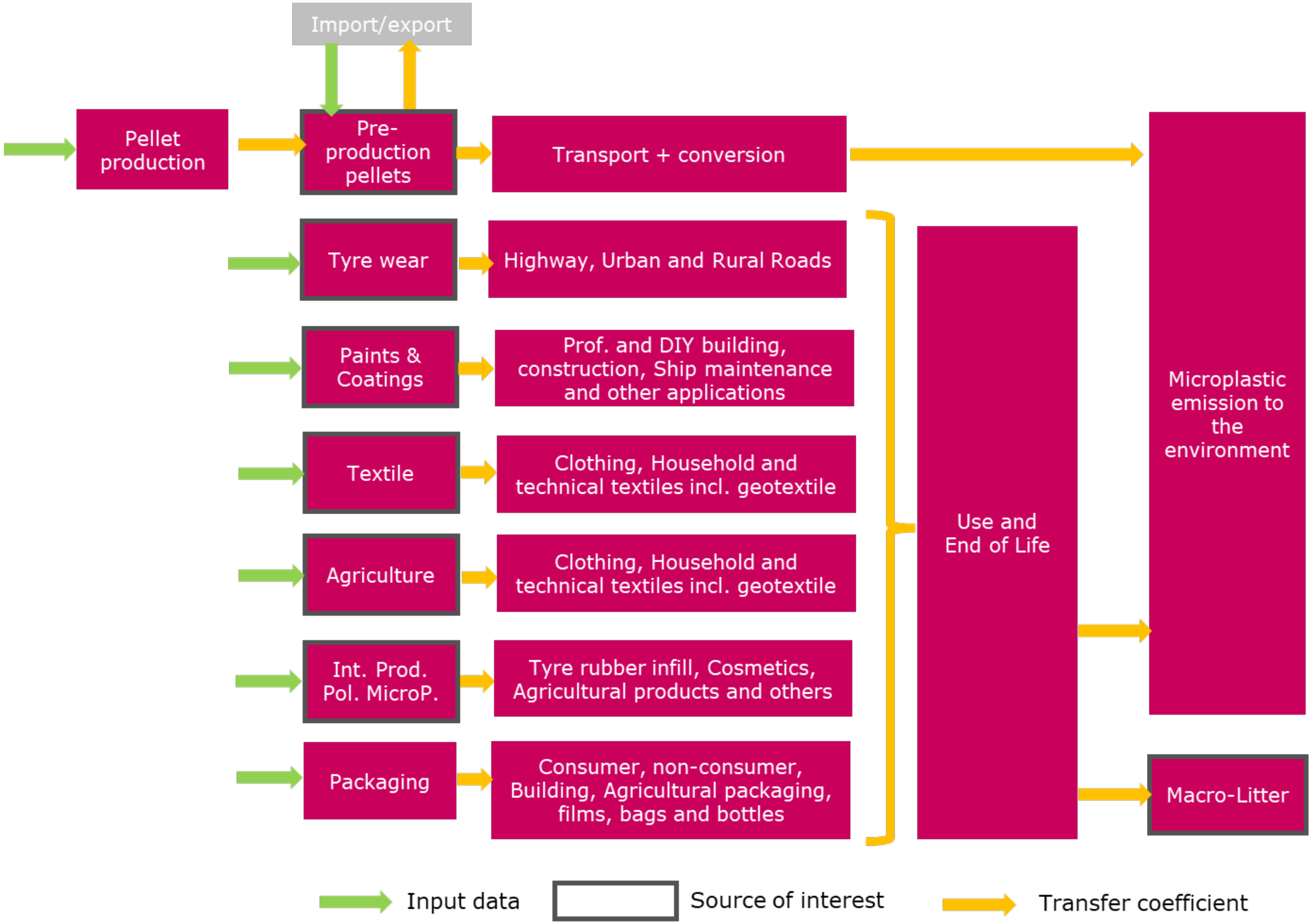


Figure 3 Simplified overview of scope of the Material Flow Analysis. (Int.Prod.Pol.MicroP = intentionally produced polymer microplastics).

Box 1 *Material flow analysis*

A material flow analysis (MFA) is a commonly used method to track the flow of a material through a system. An MFA consists of two types of elements: compartments and flows. The compartments represent various stages of the material’s life cycle (such as production, consumption, or disposal). The flows represent the movement of the material to and from compartments and are typically quantified by mass. There are three types of compartments in an MFA: flow compartments, which have material inflows and immediate outflows; stock compartments, which have material inflows and delayed outflows; and sink compartments, which have only material inflows (material accumulates here). The flow compartments that receive external inflows, i.e. inflows from outside the system boundary, are commonly referred to as ‘input compartments’. Apart from a dataset defining the external inflows, an MFA model requires a transfer coefficient dataset, which defines for each outflow the proportion of the mass inflow that flows to the next compartment. On the basis of those two datasets data, an MFA computes the mass inflow(s), outflow(s) and content for each compartment. Figure 4 shows a simple MFA to illustrate the concept.

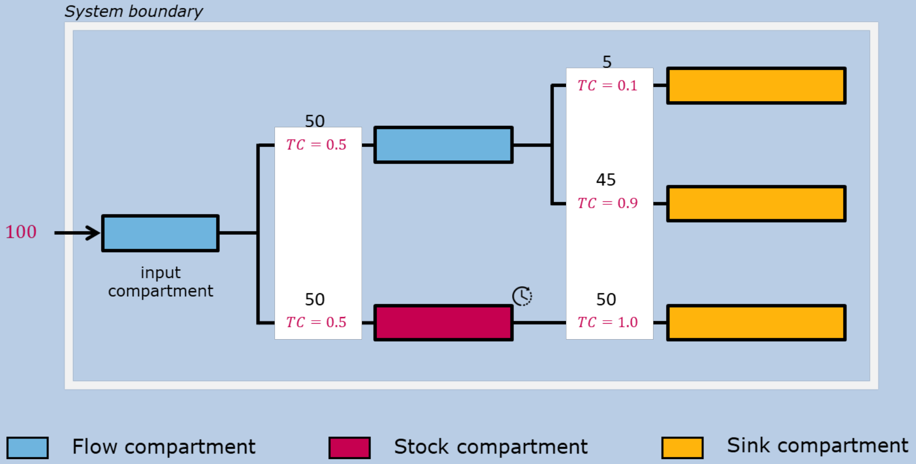


Figure 4 Simple MFA example.

An MFA model computes how the external input mass (100 here) is divided across the other compartments on the basis of the transfer coefficients (TCs) defined for each outflow.

Box 2 *Probabilistic material flow analysis*

A probabilistic material flow analysis (PMFA) is a method used to assess and analyse the flow of materials through a system, while taking data uncertainty and variability into account. The input values are randomly chosen from defined probability distributions rather than using fixed values. Uncertainty relating to a single data point is represented by a triangular probability distribution. In this distribution, the tip of the triangle represents the provided data value, while the width of the base depends on the level of uncertainty. The higher the uncertainty, the wider the base of the triangle. To accommodate data variability, a trapezoidal probability distribution can be used when two data values are provided. In this distribution, the upper left and right vertices of the trapezium correspond to the provided minimum and maximum data values, respectively. The slope of the left and right edges varies according to the uncertainty associated with the minimum and maximum data values, respectively. Figure 5 shows examples of triangular and trapezoidal probability distributions around data values.

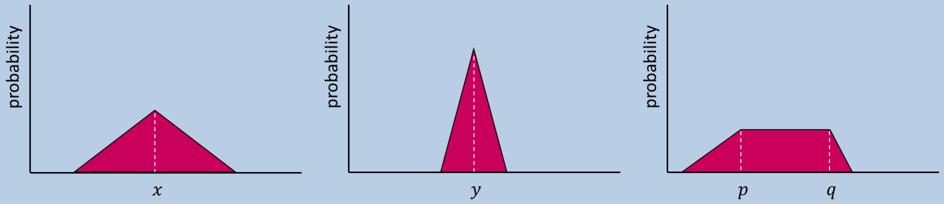


Figure 5 (a) Triangular probability distribution around a data value (x) that has a relatively high uncertainty. (b) Triangular probability distribution around a data value (y) that has a relatively low uncertainty. (c)
Trapezoidal probability distribution based on two data values (p and q) of which p has a higher uncertainty than q.

A PMFA model works as follows: first, it gathers input data by randomly choosing values from the probability distributions across the provided data values. Secondly, it computes all mass flows between the compartments, constituting the model's output. These two steps are repeated numerous times, which is called a Monte Carlo simulation. The number of Monte Carlo iterations is typically set to 10 000. This results in the generation of 10 000 distinct model outcomes. The model results are often reported along with their range and standard deviation. Thus, the uncertainty around modelled results can be effectively expressed.

Box 3 *Dynamic material flow analysis*

A dynamic material flow analysis (DMFA) is a method used to analyse the flow of materials through systems while considering changes over time. Unlike a static MFA, which provides a snapshot of material flows at a single point in time, a dynamic MFA model accounts for the accumulation and depletion of materials over time. In a DMFA model, there are stock compartments where materials accumulate. When a material enters a stock compartment at time t_0, it is not immediately transferred to the next compartment(s). Instead, only a portion (or nothing) of the material is released immediately, while the rest remains in stock. A release function specifies the fraction of material released every year from t_0 onwards. Figure 6 shows examples of both a non-dynamic MFA, in which a flow compartment immediately transfers a mass inflow to an outflow, and a dynamic MFA, in which a stock compartment accumulates material mass and releases fractions of this mass stock through time.

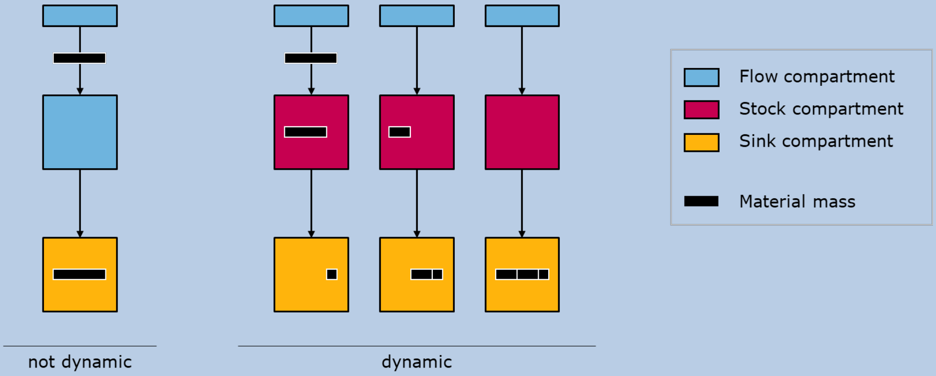


Figure 6 Example of a non-dynamic (left) and a dynamic (right) MFA.
The stock compartment in the dynamic MFA holds on to a portion of the received mass and releases fractions of it over time.

2.3 Emission estimates

2.3.1 Modelling approach: Probabilistic Material Flow Analysis

The applied MFA uses the probabilistic approach previously applied by Kawecki et al. (2018), which we have abbreviated to PMFA. This means that the uncertainty of both the input flows and the transfer coefficients are included (See Figure 5 and Box 2) on the basis of assigning scores to five data quality indicators. These five data quality indicators are: (1) geographical representativeness; (2) temporal representativeness; (3) material representativeness; (4) completeness; and (5) source reliability. Each indicator is assigned a score between 1 (very good) and 4 (very poor). The scores of the five data quality indicators are translated to triangular or trapezoidal probability distributions (see Appendix 8.1 for further details). Through a Monte Carlo simulation with 10 000 iterations, the model calculated all plastic mass flows and emissions within the system by propagation of uncertainty.

For the goal of estimating plastic emissions to the natural environment, the total plastic emission is calculated for the reference year 2019 (see *non-dynamic* in Figure 6, Box 3). This means that the emission estimate is the plastic footprint related to all plastics input into the system in

2019. This is similar to the approach taken by Kawecki et al. (2018) and by Verschoor and de Valk (2018).

2.3.2 *Output visualisation*

The results were visualised using so-called 'violin plots', which are an elegant way of indicating the uncertainty of model outcomes. The width of the 'violin' (which is lying on its side in this report) represents the frequency of data points at a certain value, while the length of the violin shows the spread of the data points.
This means that violins plots that are longer have a higher uncertainty of outcomes than violin plots that are shorter. It also means that the probability of a certain output value occurring in reality is the highest where the violin is thickest.

2.3.3 *Data sources*

The plastic flows and emissions to the natural environment were computed for the Netherlands and for Europe for the year 2019. Distinct external inflow data was gathered for the Netherlands and Europe. Some transfer coefficient (TC) values are region-specific (for instance the fraction of plastic packages littered), while others, for instance those related to process, are less region-dependent (for instance the fraction of microplastic particles released from textiles during washing). For the latter, we mostly re-used the TC values reported in the studies by Kawecki et al. (2018), Kawecki and Nowack (2019), and Kawecki et al. (2021), which had Europe and Switzerland as case study areas. Below, we will shortly describe the data sources that we used for the external inflows and transfer coefficients in the model. For further details on each of the categories, we refer to Appendix A.

2.3.3.1 Pre-production pellets

The term pre-production pellets is used for all plastics in their primary form. Input data for the EU and the Netherlands on domestic production and import of pre-production pellets was obtained from Eurostat (Eurostat, 2024).
On Eurostat, goods are divided into different PRODCOM (PRODuction COMmunautaire) categories. The PRODCOM categories included in this research largely correspond to the categories included by the European Commission (EC, 2023b), although more categories were included in this research. Another difference is that, in this research, macroplastic categories of primary plastics (such as sheets of rubber) were not included. EC reported a total input of pre-production pellets in 2019 of 80 million tonnes in the EU, while our methods yield an input of 75.9 million tonnes.

Input data was used for the following polymers: LDPE, HDPE, PP, PS, EPS, PVC, PET, ABS, PC, PMMA, PA, PUR, and Other. Data was collected for the Netherlands for the years 1995-2021, and for the EU for the years 2003-2021. Most transfer coefficients were re-used from Kawecki et al. (2019).

2.3.3.2 Tyre wear

Tyre wear is estimated on the basis of the existing approach applied by the Emission registry in the Netherlands (RWS, 2022). This means that the data for Europe is based on the emission factors derived for the

Netherlands using the method by Geilenkirchen et al. (2023). As such, the starting point of the MFA model is the released tyre wear (input in kton), which then follows various routes to the environment (directly to air, directly to road-side soil and through run-off to road-side soil and water), mainly following the study by Hoeke et al. (2024) and Sieber et al. (2020). Releases from tyre crumb used as infill are also estimated as part of intentionally produce polymer microparticles (see above); other applications of tyre rubber material (such as agricultural mats or rubber tiles) are not included in this analysis.

2.3.3.3 Paints and coatings

Domestic paint sales data relating to the years 2015-2022 was obtained for the Netherlands from the Annual Review of the *Association of Paint and Printing Ink Manufacturers* (Dutch: Vereniging van Verf- en Drukinktfabrikanten) (VVVF, 2023). The domestic paint sales for the Netherlands in 2019 amounted to 51.2 kt. For the EU, only paint sales data for 2019 was found (EC, 2023b). The paint sales in the EU for 2019 amounted to 2326 kt. For both the Netherlands and the EU, it is assumed that paint only contains acrylic.

The transfer coefficients of the flows relating to paint and coatings were obtained from the study by Verschoor et al. (2016). When no data on transfer coefficients was available, assumptions were made.

2.3.3.4 Textiles

Textiles contain plastic polymers. In this study, textiles were divided into three main categories:

- clothing;
- household textiles;
- technical textiles.

Household textiles and technical textiles have six and seven subcategories, respectively. The annual consumption of textiles for all (sub)categories were calculated on the basis of the fractions reported by Kawecki and Nowack (2019). A fraction of 63% of consumed textiles in 2019 is synthetic, this is based on estimates by Boucher and Friot (2017) and EEA (2019).

The total textile consumption in 2019 in the Netherlands amounted to 646 kt (CBS, 2021) of which 407 kt are plastic polymers. In 2019, the textile stock in the Netherlands consisted of clothing (7.3%), home textiles (7.1%), and technical home textiles (26.6%) (CBS, 2021).

For Europe, the total textile consumption was estimated at 13 256 kt in 2017, of which 8351 kt are plastic polymers. This was based on a consumption of 26 kg per person (reported by the European Environment Agency (EEA, 2019)) and a total of 511.8 million inhabitants (Eurostat, 2017).

The use of geotextiles (a sub-category of technical textiles) in 2022 in the Netherlands (11.4 kt) and in Europe (200 kt) were obtained from the study by Voskamp and Retzlaff (2022).

The transfer coefficients of the flows relating to textile were adopted from Kawecki and Nowack (2019) and the FFact report (FFact, 2020). For the release of microplastic fibres to wastewater during washing, the results from seven experimental studies were combined (Belzagui et al., 2019; De Falco et al., 2018; Hartline et al., 2016; Hernandez et al., 2017; Napper and Thompson, 2016; Pirc et al., 2016; Sillanpää and Sainio, 2017).

2.3.3.5 Agriculture

The mass of agricultural plastics consumed in Europe in 2018 and 2019 was obtained from APE Europe (‘Statistics - APE Europe’, n.d.). In 2019, 695.5 kt of plastic was consumed in agriculture in the EU. This mass was scaled to the Netherlands by multiplying by two different fractions to get a high and low estimate of the agricultural plastic consumption for the Netherlands in 2018 and 2019. For 2019, this yields a total input value of between 22.9 and 46.7 kt.

Transfer coefficients from the Agriculture compartment to each of the subsequent compartments (Agricultural greenhouse films, Agricultural mulching films, Agricultural pipes and Agricultural other) was calculated using fractions from an FAO report on sustainability of agricultural plastics (FAO, 2021) for the EU, and Urbanus et al. (2022) for the Netherlands. Transfer coefficients from these compartments to all following compartments were re-used from Kawecki and Nowack (2019).

The lifetimes for the agricultural greenhouse films and Agricultural pipes compartments are taken from Kawecki and Nowack (2019).

2.3.3.6 Intentionally produced polymer microparticles

EU input data was retrieved from RAC and SEAC (2020). The fractions of polymers in the PCCP and Detergents and maintenance products compartments were obtained from Scudo et al. (2017). Other polymer divisions are assumptions made by RIVM.

Input data for the Netherlands was calculated using three scaling factors: population, agriculture and oil-gas. One of these factors was applied to each of the compartments to obtain the input data for the Netherlands.

Transfer coefficients (TCs) were obtained from Plastic Packaging Composition 2011 (2013), Kawecki and Nowack (2019) and Hoeke et al. (2024). Information from the WRAP reports was used to divide the total mass of packaging across various sub categories, and information from Hoeke et al. (2024) was used for TCs pertaining to infill material for sports fields. Other TCs were reused from Kawecki and Nowack (2019).

2.3.3.7 Macroplastics

Some sources do not just emit microplastics, but macroplastics, too. The potential formation of microplastics from macroplastics in the environment was not included in the model. Sources that emit macroplastics are agriculture, textiles, packaging, and paint.

Macroplastics are emitted in agriculture when films are not entirely removed from agricultural soil or when the collected agricultural plastic waste is not properly stored. For textiles, macroplastics are assumed to be emitted when personal care products (i.e. tampons, wet wipes) are flushed through the toilet, when technical textiles are not properly removed from the soil or when clothing and home textiles are dumped, based on Kawecki and Nowack (2019). Packaging is mainly emitted to the environment through dumping. Lastly, paint macroplastics are emitted when dried paint in cans is lost due to a leak in the waste collection system. Specific customs in the Netherlands are not taken into account separately, such as the application of recycled building materials to paths in nature areas, which often contain impurities, such as plastics.

2.4 Solution-focussed participatory approach

The following steps were followed to include experts in the research as described in Section 1.3:

1. Desk research: compiling an overview of the most important sources of microplastics and the mitigation measures for those sources;
2. Expert mapping: identifying experts from universities, NGO's, knowledge institutions, consultancies and government organizations (Table C1) for the Dutch and European context, covering expertise of different microplastics sources.;
3. Online expert workshop (21 June 2023): identifying sources, mitigation measures and prioritising mitigation measures according to feasibility and effectiveness (see Appendix C fordetails).

A second stakeholder workshop that was based on the modelling of mitigation measure effectiveness would have contributed to further refinement of the modelling approach and increased the relevance of each mitigation measure. However, due to resource limitations and delays, this was not possible within the current project.

During the online workshop, the experts (see Appendix C) indicated the most important principles of designing measures to reduce microplastic emissions. All emphasised the need to take preventative measures and to do so close to the source, from a system's perspective and based on evidence.

2.5 Mitigation measures and their effectiveness

Below, we will describe how the second goal of the study is realised, i.e. to estimate the impact of mitigation measures on reduction of emissions. An inventory of mitigation measures was based on literature and an expert workshop followed by a prioritisation in order to select measures for further analysis using our modelling approach.

First, we describe how measures were identified in a participatory manner and second how these mitigation measures were modelled.

2.5.1 Method for selection and definition of mitigation measures

During the expert workshop, the 26 participating experts prioritised measures to mitigate emissions of microplastics according to sources. For some sources, the measures had already been identified (see

Section 1.4) while for others, additional measures were identified during the workshop.

Prioritisation of measures was achieved on the basis of feasibility and effectiveness. Per source, experts gave the measures a score of 1, 2, or 3 on the basis of the following:

Effectiveness: to reduce MP
1. High effectiveness;
2. Medium effectiveness;
3. Low effectiveness.

Feasibility: to implement long or short term
1. Easy;
2. Possible, but some effort required;
3. Difficult, e.g. requires significant effort.

For this participants were asked to take a broad view on feasibility including technical and economic feasibility.

These scores were then added up, and the measures were ranked on the basis of the highest combination of effectiveness and feasibility scores. This resulted in an overview of measures identified and how they were scored during the workshop, which can be found in Appendix C.

Participants reflected that it would be useful to group the measures in a conceptual framework for further study. This was achieved by grouping the measures according to the circular economy waste hierarchy, also known as R-ladder, a tiered model with circularity strategies, including reduce, reuse, and recycle (Kishna and Prins, 2024; Van Buren et al., 2016). This is further explained in the next section (2.5.1.1).

2.5.1.1 Method for measure classification

Mitigation measures were classified to identify (i) the hierarchy in terms of contribution to a circular economy, and (ii) where in the system a measure can be carried out to reduce emissions to the environment.

Hierarchy in circularity
Where in the production chain the measure has an effect according to the main circularity strategies has been defined by the Dutch Environmental Assessment Agency (Kishna and Prins, 2024) and the Zero Pollution Hierarchy of the European Commission (European Commission, 2021). The higher the strategy, the more effective in its contribution to a circular economy or tackling pollution.

The following classification is used:
- **Narrow the loop (refuse, rethink, reduce)**: Use fewer plastics, preventing or reducing the use of plastic as a raw material
- **Slow the loop and extend lifetime (re-use, repair, refurbish, remanufacture, repurpose)**: The product is better made or repaired more often, but we do not include changes in the overall use and end-of-life losses, just that the lifetime of the products is increased.

- **Close the loop (Recycle and recover):** Processing and reusing materials. When more goes to recycling, less goes to incineration/recovery. In recovery, energy is won back by incinerating the materials. As the materials are then permanently lost to the product chain, recovery does not fit in well with the circular economy and should be avoided as much as possible (Kishna and Prins, 2024)

System phase
A classification is used to indicate where in the system a measure takes place. The following classification is used:

- **Limit source:** The measure ensures the microplastic cannot end up in the environment
- **End-of-pipe**: Filter out microplastics before they end up permanently in environment
- **Clean up:** After emission to the environment, it is possible to clean it up. Not all these measures can be implemented in the model. It is currently possible for street cleaning of microplastics from tyres, but not for cleaning up litter.

In taking measures, the focus is on prevention and limiting emissions at the source. This is also in line with European Union policy as shown in the Zero Pollution Action Plan, see Figure 2(European Commission, 2021).

2.5.1.2 Further workshop input

During the workshop, several important remarks were made about further study and work on implementing the measures:

- Measures taken at the source, or preventative measures, are the most effective ones.
- Some measures overlap and some measures are prerequisites for others.
- Participants interpreted feasibility in different ways. Most scored on technical feasibility, but some also took financial or political feasibility into account. Participants were asked to take a broad view on feasibility.
- The measures that can be taken relatively quickly and easily are often not very effective end-of-pipe solutions, whereas the more effective measures take more time.
- The most effective measures are often the hardest to implement for several reasons, among which political reasons. It is important to look beyond low-hanging fruits, too.
- Some measures might be steppingstones for other measures.
- When formulating measures, it is important to be as specific as possible with regard to how a certain outcome (for instance using sustainable fibres, changes in products, reducing use) will be achieved, as this will determine effectiveness and feasibility. For example, is it achieved through regulations/bans, economic incentives/penalties or through voluntary initiatives?
- The model does not account for all kinds of trade-offs. For example, if we limit the use of textiles containing plastics and apply natural fibres, this contributes to the reduction of microplastic emissions, but natural fibres also have an environmental impact.

- Other possible sources that became clear from the workshop:
    - During the workshop with experts, a few other possible sources of microplastics were mentioned that require further research to determine their respective sizes. The following sources were mentioned:
        - Microplastics abrasion from windmills. Potentially a smaller source
        - Use of recycled textile fibres in equestrian centres. Potentially a smaller source.
        - Plastic blocks are used in waterways that are made from (recycled) polyolefins, which is potentially a larger source (de Visser et al., 2022).

2.5.2 *Selection of measures for modelling*

Categorisation of measures in the manner described above helped to group similar measures together. To select measures for modelling, the longlist was reduced to three measures for each source, covering various circularity strategies and the way the microplastics end up in the environment. Not all sources were included in the modelling, for instance soap capsules were not. The measures were selected from the longlist (Appendix C) and described in the following manner:

- Excluding measures from the longlist, on the basis of the following reasons:
    - Measures that are not considered appropriate for EU interventions or that overlap or interact with existing EU initiatives, such as a ban on intentionally added microplastics;
    - Measures that are aimed at R&D or have a low Technology Readiness Level (TRL), such as research into self-healing plastics;
    - Measures that scored low on feasibility and/or effectiveness;
    - Measures that require further cost-benefit analyses, such as application of recycled content, which may increase microplastic emissions during its life-time.
- Describing measures for assessment:
    - Measures were formulated, sometimes on the basis of a grouping of measures with a similar aim, such as reducing materials. For each measure, it is described how the measure works or could be implemented.
- Implementing the measures into the model:
    - Measures are described in such a way that they can be implemented into the model;
    - To compare various mitigation measures without taking feasibility into account, an a priori 30% feasibility of the reduction or improvement factor is applied to all measures. For instance, the lifetime is increased by 30%, the use of plastics in products is reduced by 30% or the filtering efficiency for removing plastic from a certain waste stream is improved by 30%. The resulting reduction in emissions can thus be seen as a potential reduction based on this 30% feasibility used for all measures except the reduction of intentionally produced microplastics, for which because of the existing ECHA restriction a 100% feasibility is used.
    - This 30% is an arbitrary value, but does coincide with the EU goal of a 30% reduction of microplastic pollution of the

environment by 2030, as was established by the Zero Pollution Action Plan of the European Commission (European Commission, 2021).

Pre-production pellets
For this source of microplastic pollution, the European Commission published a proposal of measures after the workshop we held for this study (EC, 2023e). For the measures that were quantified, we also took this legislation into consideration.

1. End-of-pipe: Reduce pellet spillage relating to transport on land or sea, for example due to:
    a. Improved packaging for transport: Airtight and puncture-resistant through voluntary agreements or mandatory requirements;
    b. More indoor handling of pellets: indoor spills are much easier to clean up;
    c. Introduction of better management practices to cause fewer spills during pellet handling.
2. End-of-pipe & clean-up: Reduce pellet spillage at industrial plants through:
    a. EPR systems throughout the chain;
    b. Mitigation and clean-up measures can take the form of filters, vacuum systems to remove accumulated pellets, and tools for immediate cleaning (shovel, broom, brush, vacuum cleaner) through regulatory requirements;
    c. Mandatory requirements to prevent and reduce pellet losses with lighter requirements for micro and small companies, for example through:
        i. The creation and publication of internal procedures such as defining organisational responsibilities, a pellet loss prevention policy with pellet loss prevention objectives, a regular risk mapping exercise and corresponding risk management assessment at site level;
        ii. Competence, training and awareness of staff to contain and clean up spills including maintaining a record of spills;
        iii. Operational controls including preventive, mitigating and clean up measures and equipment.
3. Improve wastewater treatment at industrial plants to reduce the losses to surface water from industrial plants through:
    a. Filtering the water at production site.

Tyre Wear

4. Limit source: less tyre wear released, for instance due to:
    a. Speed reduction, adjustment of speed limit;
    b. Less overall mileage due to, for example, road pricing, increase in public transport or making it more attractive;
    c. Introducing a tyre pressure monitoring system (TPMS) for old cars and other activities to facilitate consumers in keeping an optimal tyre pressure, such as awareness campaigns;
    d. Alternative tyre design, for example through introducing legal thresholds for tyre wear and integrating a tyre label into an energy label, reducing abrasion rate, banning winter tires in the summer;

    e. Road design requirements (for instance, reducing high-wear locations, adding abrasion rate criteria);
    f. This also includes a reduction in release at the source, such as TWP capturing devices at the tyre/vehicle.
5. End-of-pipe: improved run-off treatment for rural and highway road systems:
    a. Treatment of road run-off increases by adding waste water treatment step to the rural and highway road system.
6. Clean-up: street cleaning efficiency is improved:
    a. More frequent sweeping of streets

Paints and coatings (for DIY and professional)

7. Narrow the loop: reduce plastics used in paint and thus microplastic emission through:
    a. Paint innovation: Improving the wear resistance of the paint; replacing persistent synthetic polymers with more environment-friendly ingredients, such as mineral-based, powder, self-healing biodegradable polymers
    b. Improving the method of paint application so; that less paint is used;
    c. Reducing the amount of paint used, for instance through use of equipment, by using other materials;
    d. Recycling of left-over paint.
8. End-of-pipe: Lower percentage of in-use emissions of plastics in paint, by increasing the time the paint stays applied:
    a. Paint innovation: Improving the wear resistance of the paint;
    b. For Do-it-yourself (DIY): Pre-treatment of the surface that needs to be painted (sanding and priming) to prevent untimely wear;
    c. Legal warranty period for paint.
9. End-of-pipe: Reduce losses during application of paint by:
    a. Preventing the emission of paint to wastewater, for example through a brush rinsing awareness campaign; Preventing the rinsing of brushes and rollers in the sink.
10. Clean-up: better recovery of paint at the end of life, for example in renovation work, due to:
    a. Improved technique for sanding and replacing old sanders;
    b. Using methods that limit the spreading of dust during the removal of coatings;
    c. Developing products (catalysts) that enhance the end-of-life degradation of paint (this is not really part of the MFA, but could be seen as part of reducing emissions at the end of life.

Textiles – clothing & household

11. Narrow the loop: Less plastic used in clothing and household textiles; this can be due to:
    a. Design & production principles, for example limiting certain fabrics (e.g. fleece) and glitter;
    b. Reducing synthetic materials or adjusting the percentage of plastic in textiles, instead applying natural fibres and materials.
12. Slow the loop: Higher-quality products. This means increasing the lifetime of textile products through:
    a. Reducing glitter textiles’

   b. High-quality clothing: has the same emission of microplastics but takes longer to be released;
   c. This measure should also reduce the amount of clothing used, and thus contributes to narrowing the loop;
   d. Consumer awareness campaign on buying higher-quality clothes.
13. End-of-pipe: Reduce emissions to wastewater, for example through:
   a. Washing machine filters;
   b. Regulations for washing machines, for example to add instructions for washing with liquid detergent and at a low temperature;
   c. Prewashing;
   d. Improving removal from waste water treatment plants (WWTP).

Textiles – technical
The workshop focussed on geo-textiles (see Appendix C). But the measures identified are applied to all types of technical textiles as much as possible. We did not assess the application of recycled content or of additive chemical release. This requires further research.

14. Narrow the loop: Adjust percentage of plastic in technical textiles or limit use through:
   a. Limiting use to essential or specific application (for instance hydraulic application);
   b. Using more natural materials that degrade after the lifetime, for example through obligations.
15. Slow the loop: Improve maintenance in order to reduce in use releases.
16. Close the loop: stimulate recovery and recycling at the end of life through:
   a. Paying for lost weight;
   b. Registering geotextiles in works;
   c. Increasing percentage of recycling.

Agriculture (excluding textile)
17. Narrow the loop: decrease microplastics in agricultural plastic through:
   a. Promoting eco-friendly materials, or durable materials resistant to UV, toxic free materials;
   b. Limiting use to essential use;
   c. Regulating the type of fibre or polymer used.
18. Close the loop/ end-of-pipe: Encourage reuse and recovery of agricultural textile, for example through:
   a. Depositing return scheme to encourage reuse and recovery;
   b. Paying for weight that is lost;
   c. Redesigning to make reusable – not burying them in the soil.

Macroplastics and packaging
19. Narrow the loop: Measures to restrict plastic products:
   a. Restricting single use / non-essential products;
   b. Refusing, reducing and redesigning plastic products;

    c. True pricing for virgin plastic;
    d. Reducing material complexity.
20. Slow the loop: Reuse plastics so that they are longer in the system through:
    a. Innovative design
    b. Improved packaging concepts
    c. Return / deposit systems
21. Close the loop / end-of pipe: Capture microplastics at recycling plants through improved waste management systems, for example filters
22. End-of-pipe: Clean-up in the environment through litter clean-up at roadsides, park, rivers.

Other

23. Restrict use of intentionally produced polymer microparticles as intended by the ECHA restriction.

Table 4 Overview of selected mitigation measure classification and their model implementation.

ID	Source category	Description of measure	Measure type	Emission phase	Model implementation
1	Pre-Production Pellets	Prevent spillage transport (better packaging, improved storage)	Close the loop	End-of-pipe	Reduce TC to pellet losses transport
2	Pre-Production Pellets	Prevent spillage industrial plants (mitigation & clean-up)	Close the loop	Clean-up/end-of-pipe	Reduce TC to pellet losses industrial plants
3	Pre-Production Pellets	Clean-up of water flow coming out of industrial plants	Close the loop	End-of-pipe	Reduce TC from industrial stormwater (micro) to surface water (micro)
4	Tyre Wear	Lower wear of tyres	Narrow the loop	Limit source	Input value decrease
5	Tyre Wear	Capture road runoff at highway and rural road networks	Close the loop	End-of-pipe	Reduce TCs to environment
6	Tyre Wear	Improved street cleaning and overall reduction of Tyre Wear Releases	Close the loop	Clean-up/end-of-pipe	Increase TCs to road cleaning
7	Paint	New types of paint (less plastic) / reduce paint use	Narrow the loop	Limit source	Input value decrease
8	Paint	Increase lifetime	Extend lifetime	-	Not implemented
9	Paint	Reduce losses at time of application, due to rinsing etc.	Close the loop	End-of-pipe	Reduce in use emissions
10	Paint	Better recovery EOL paint	Close the loop	End-of-pipe	Reduce TCs to air and water
11	Clothing + home textiles	Less plastic in textiles (more natural materials)	Narrow the loop	Limit source	Input value decrease
12	Clothing + home textiles	Higher-quality products	Extend lifetime	-	Not implemented
13	Clothing + home textiles	Reduce emissions to wastewater	Close the loop	End-of-pipe	Decrease TC for use emissions to waste water (see details on sheet)
14	Technical textiles	Reduce percentage of plastic in technical textiles or limit use	Narrow the loop	Limit source	Input value decrease
15	Technical textiles	Stimulate recovery and recycling at end of life	Close the loop	End-of-pipe	Decrease TC to dumping and other losses

ID	Source category	Description of measure	Measure type	Emission phase	Model implementation
16	Technical textiles	Improve maintenance in order to reduce in use releases	Close the loop	End-of-pipe	Decrease loss from in use emissions of agro- building- and geo-textiles
17	Agriculture	Encourage reuse and recovery	Close the loop	End-of-pipe	Increase TC to agricultural plastic recycling, decrease TC to incineration
18	Agriculture	Promote eco-friendly materials (bio-plastics)/only essential use of plastics	Narrow the loop	Limit source	Input value decrease
19	Macroplastics	Restrict single/non-essential use to reduce single use plastic consumption	Narrow the loop	Limit source	Input value decrease
20	Macroplastics	Longer use of plastic products through innovative design/ deposit systems	Extend lifetime	-	Not implemented
21	Macroplastics	Capture MPs at recycling plants (end of pipe)	Close the loop	End-of-pipe	Decrease TC to environment from each waste type of recycling[a]
22	Macroplastics	Clean up in the environment	Close the loop	Clean-up	TC for losses linked to environmental sinks are reduced
23	Intentionally produced microplastics	Restrict use as aimed for by ECHA restriction (derogation periods etc. not accounted for)	Narrow the loop	Limit source	Input value decrease 100%

a. Meaning transfer to incineration increases

2.5.3 *Modelling approach: Dynamic Probabilistic Material Flow Analysis*

To estimate the impact of mitigation measures on the reduction of plastic emissions to the natural environment, the time dimension was taken into account. The plastic flows were calculated for measures implemented in 2025 and the resulting changes in emissions for 2030 and 2050 compared to the baseline. The baseline is built up of the same inputs and transfer coefficients as applied to the total emission estimates (Section 2.3). The main difference is that product lifetimes are taken into account, which has an effect on when end-of-life emissions and in-use emissions occur. Apart from flow and sink compartments, the MFA framework included stock compartments for plastic product categories that had a considerable lifetime (See Box 3). Examples of such categories are ‘agricultural plastic films’ and ‘clothing’, whereas the use of ‘single-use food packages’ was not modelled using stock compartments. The delayed material outflows from stock compartments mimic the continuing in-use and postponed end-of-life emissions. The DPMFA model was used to evaluate the emission reduction potential of microplastics for each mitigation measure. We calculated the percentage change in emission of the mitigation scenario compared to the baseline. Each mitigation measures is implemented based on a generic 30% level of efficiency or feasibility. This means that the potential reduction in emissions is not an absolute or realistic estimate of the effect the measure could have when implemented. However, this approach is useful for comparing the different measures to each other across the different emission sources. Further details are described below. The results of this approach can be found in Chapter 4.

2.5.4 *Modelling approach: Mitigation measures*

To calculate the emission of a mitigation measure, a new model scenario was created, changing the input and transfer coefficients. For each measure, the DPMFA model was run, using a time period from 1950 to 2050 and a thousand runs. The model was run from 1950 to include legacy emissions from products with long lifetimes as well. These model scenarios for each mitigation measure where then compared to the baseline, in which the system was the same as for the emission estimates (Section 2.3), but with the addition of product lifetimes and stocks.

From a modelling perspective, the mitigation measures in Table 4 can be divided into three categories: input alterations, lifetime alterations and transfer coefficient alterations. By increasing or decreasing the original values, the effectiveness of mitigation measures can be calculated. To be able to compare the measures with each other across microplastic sources, a factor of 0.3 (30%) was chosen for increasing or decreasing each value. Although this is an arbitrary value, it does correspond to the EU aim to reduce microplastic release to the environment by 30% in 2030 (EC, 2024).

2.5.4.1 Input alterations

Data from OECD (2022) plastics outlook is used to project the changes in plastic consumption up to 2050. To calculate input reductions, all projections from 2025 onwards were multiplied by 0.7 (1-0.3). These new projections were used to calculate the emissions for a 30% input reduction.

2.5.4.2 Lifetime alterations

To simulate longer use of products, the lifetimes of certain product groups were increased with 30%. This was attempted by reducing the fraction of emitted material in each year by 30%, and adding the difference to the next.. This only resulted in spreading the in-use emissions over a longer time period. However, the results from these calculations were not deemed useful because there was no feedback to reduced demand in time due to the longer lifetime. This needs further work and as such, the model results for the extended lifetime measures are not reported (Measures 8, 12 and 20).

2.5.4.3 Transfer coefficient alterations

Transfer coefficient alterations depend heavily on the source for which the measure is carried out and on the measure itself. Depending on the measure, existing transfer coefficients are increased or decreased by 30% and/or new flows are added between existing compartments. For most of these measures, multiple transfer coefficients were adjusted. Detailed information on the implementation of all measures can be found in Appendix C, Section 9.3.

2.5.4.4 Emission reduction potential of measures

We report values relative to the respective source (i.e. reduction of release from tyre wear only) and relative to total emissions of microplastics and plastics from all sources together. The model itself is applied in a probabilistic manner resulting in a certain numerical uncertainty of the results, largely dependent on the number of runs being conducted. In a test with 1000 runs, a numerical spread of up to about 2.5% (1.8% in 2019, 1.5% in 2030, 2.5% in 2050) was observed when considering one source, and up to about 0.12% (0.08 in 2019, 0.08 in 2030, 0.12 in 2050) when observing all sources together. This spread was calculated by running the source agriculture three times, and comparing this data to the baseline for 2019, 2030 and 2050.

The emission reduction potential of mitigation measures is largely dependent on the degree to which a measure is realised: For instance does promotion of a non-polymer alternative result in a change in application of polymers by 10 or 50%? Here, we implement all measures at a 30% degree in order to disregard the measure specific efficiency or feasibility; as such follow-up studies should refine these values on the basis of feasibility. Only then can realistic estimates be made regarding future microplastic emissions.

3 Emission estimates

The largest source of microplastics to the environment (soil, water and air) is tyre wear, closely followed by pre-production pellets and macroplastics. Only after fragmentation will these macroplastics contribute to the microplastics load in the environment.

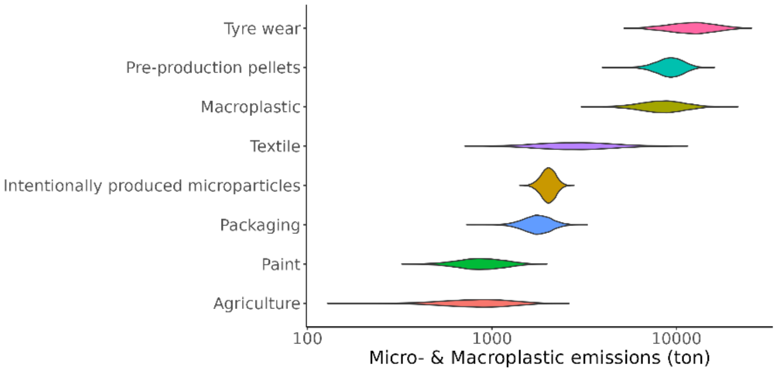


Figure 7 Plastic emissions to the environment for 2019 in the Netherlands.
The thickness of the curve indicates the frequency of data points: thicker means less uncertainty (See paragraph 2.2.2 for explanation of violin plots).

Several other studies have already highlighted that tyre wear and potential litter fragmentation are some of the largest sources of microplastics emitted to the environment in the Netherlands (Urbanus et al., 2022; Verschoor and de Valk, 2018). Pre-production pellets specifically stand for the losses during production of polymer feedstocks (virgin and recycled) and manufacturing plastic products. Although these losses are taken into account in several other studies, the present study included a novel approach to include as many potential polymer types as possible, even more than are currently part of the EU impact assessment (EC, 2023b).

In comparison to past estimates of microplastic emissions, a large difference with this overview (Figure 7) is the allocation of emissions to a specific source. For instance, in the previous RIVM study (Verschoor and de Valk, 2018), several intentionally produced microplastics were reported on separately, but not all. Also, in the study by Urbanus et al. (2022), only a few categories of intentionally produced microparticles are considered as part of the release of primary microplastics. Where past studies on litter usually only consider packaging, contributions from agriculture and textile applications are included here. For more details, see the relevant section on each emission source below.

Plastics (micro and macro) end up primarily in soil (~80%) compared to 12% in water and 8% in air. The distribution is largely dependent on the source and on the route plastics take to the environment (Figure 8). It had already been reported (Rutgers et al., 2022) that overall, land-based emissions are larger than emissions to water and air. However, it is important to realise that following emission to soil, part of these microplastics will still contribute to plastics in water due to environmental fate and transport processes (Quik et al., 2023).

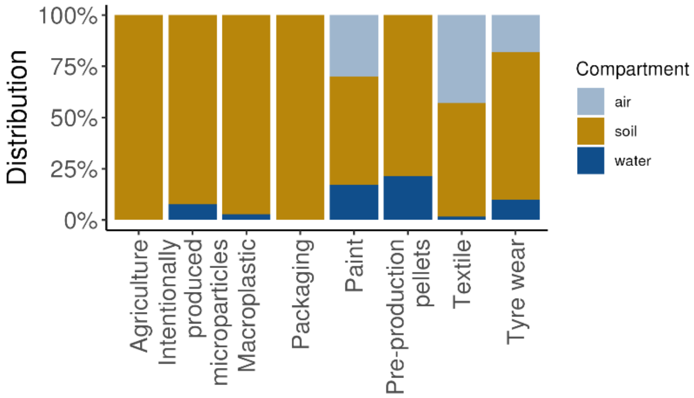


Figure 8 Emissions to water, soil and air.

3.1 Pre-production pellets

Pre-production pellets are polymer particles (flakes, powders, nurdles etcetera) that are being produced from virgin or recycled polymer feedstocks. This source amounts to an average emission of 9300 ton (6900 – 12 000 t) to the environment, to which various sources contribute (Figure 9). Handling of virgin pellets at industrial plants and overland transport are the largest sources, although the loss fraction remains uncertain. Earlier, Verschoor and de Valk (2018) estimated pellet losses of about 1000 ton to water alone, which is about half of the 1800 ton (1100-2700 t) estimated here. Although that study used relatively high loss rates (0.01% to 0.1%) without distinguishing transport, conversion and recycling, a lower result was obtained due to a much lower inflow of pellets, 1.9 megaton compared with 11 megaton in this study. Also, the EU impact assessment of pre-production pellet emissions (EC, 2023b) applies relatively high TCs for transport losses, up to 0.12%. Although these types of estimates are scarce, we applied the ones available from two studies ranging from 0.002% to 0.05%. Full details are available in Appendix A.

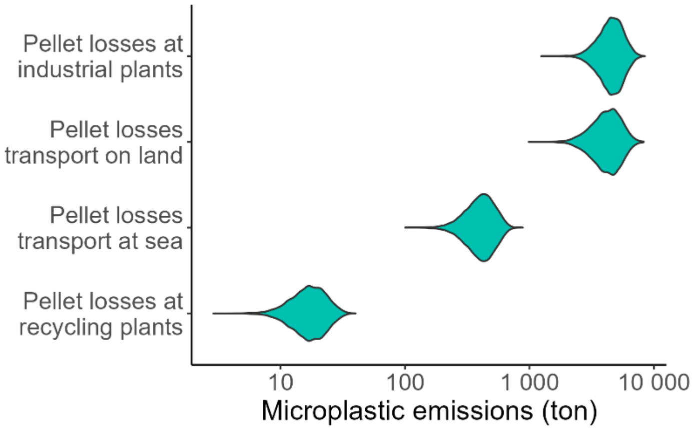


Figure 9 Pre-production pellet emissions coming from industrial plants, recycling plants and from handling and transport on land and at sea.

The microplastic emissions from pellets mainly derive from domestic production and import of polymers, while a small part is due to recycling of microplastic products as they are being prepared for further use.

3.2 Tyre wear

Microplastics from tyre wear amount to about 12 500 ton (7500 – 19 000 t). When comparing the magnitude of tyre wear particle (TWP) release to the environment, several studies have indicated similar quantities. For instance, the previous RIVM estimate indicated ~2000 ton/a release to water for 2015, which is similar to this estimate for 2019 (Figure D1 in Appendix D). Equally important is the amount of TWP emitted to air, 1800 ton (880 – 2900 t).
One of the most recent studies on tyre-related emissions in the Netherlands reported an emission to the environment of 7800 ton TWP in 2021 (Hoeke et al., 2024). This is at the lower end of the uncertainty range of the estimate reported here. In another recent study, a much lower release of tyre-related emissions was reported, amounting to about 2600 ton/a (Urbanus et al., 2022). Different scopes and approaches to estimating emissions are likely to have caused this, a detailed analysis of these was not possible.

About 36% of tyre wear does not reach the environment and is eliminated by road cleaning or runoff water treatment. Water treatment plays the largest role in urban areas, whereas road cleaning comprises a large part of elimination from highways due to the use of ZOAB in the Netherlands. The lack of data on efficiency of ZOAB road cleaning accounts for most variability in the tyre wear release to the environment (Figure D11) and small differences in our assumptions are likely to cause the difference between these estimates and those by Hoeke et al. (2024).

3.3 Paints and coatings

Paints and coatings contribute about 900 ton (530 – 1400 t) to total microplastic emissions to the environment (Figure 7), out of which roughly equal amounts go to air, soil, and water (Figure 8). Verschoor and de Valk (2018) estimated a similar emission of approximately 700 ton to water and soil. However, this applied to 2014, when almost

50% higher market sales of paint were reported. This indicates that if the paint release based on the same study is combined with the waste management system as implemented by Kawecki et al. (2019, 2021), a slightly higher emission is estimated. The higher overall environmental emission estimate for this study lies in the inclusion of separate emissions to air and soil.

Even though these emission estimates are relatively high, paint is not the largest source of microplastics, as was reported by the recent impact assessment study by the European Commission (EC, 2023b). Not many other studies have reported on paint so far, and it is recommended to look further into the release due to wear and maintenance in order to better understand paint microplastic distribution in air, soil and water.

It is estimated that about 0.49 ton (0.12 – 0.97 t) of paint remains unused and is discarded as dried up paint, resulting in the emission of macroplastics.

3.4 Textiles

Textiles make up a large source of microplastic emissions to the environment, 3100 ton (1400 – 5900 ton), mostly due to so called wear and tear, although there is a lot of uncertainty regarding its quantification. Overall, technical textiles contribute the most: On average ten times as many microplastics are released from technical textiles than from clothing and household textiles *Figure 10*.

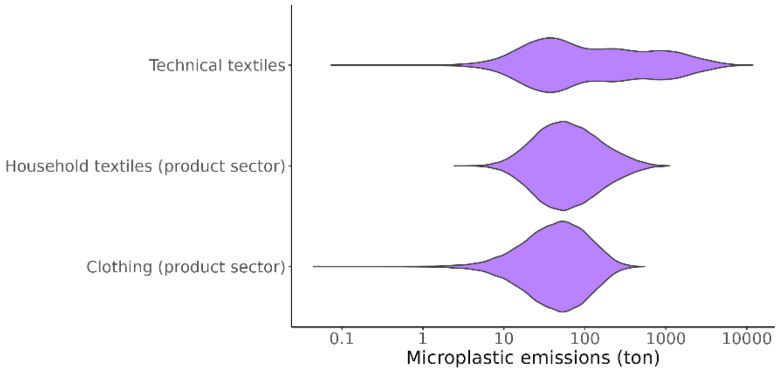


Figure 10 Emission of textile microplastics to the environment coming from technical, household and clothing textiles.

Verschoor and de Valk (2018) estimated a similar amount of microplastic release from clothing, taking into account they only considered release due to washing. Urbanus et al. (2022) reported an annual release of microplastics from textiles of about 100 ton, also taking into account technical textiles, which have a rather long lifespan. This makes it difficult to compare these findings to our estimate, which is based on consumption of textile products in 2019 and all related wear independent of lifetime. It is clear that, for instance, clothing and household textiles, which have much shorter lifespans than average products, are in the same order of magnitude as the Urbanus et al. (2022) estimate.

3.5 Agriculture

A lot of polymers are applied in agriculture, but emissions are the lowest, 880 ton (390-1500 t), compared to the other 7 sources defined in this study. The emissions of microplastics are largely due to losses during the use phase, for instance wear and tear of agricultural films, and mostly end up in the soil. Approximately a similar amount of plastic is emitted as macroplastic. Most applications are considered, such as greenhouse films, mulching, pipes and various other applications. Agrotextiles, intentional microplastics and macroplastics are included in the other respective categories.

One of the first studies to include agriculture in the assessment of microplastic releases to the environment in the Netherlands was Urbanus et al. (2022). They reported a similar annual estimate (~800 ton/a), which was the third highest after car tyres and packaging. Two important differences from this study are the time-dependent estimate, which results in lower annual (ton/a) emission for products that have a longer lifetime, and a different allocation of emissions to sources, for instance per sector, compared with the categories defined here (such as inclusion in agricultural application or intentional microplastics).

3.6 Intentionally produced polymer microparticles

Intentionally produced polymer microparticles make up the fourth largest source of microplastic emissions to the environment (2000 ton (1700 – 2300 t)). The largest contribution is from application in agriculture, 940 ton (710-1210 t) (such as controlled-release fertilisers) followed by infill material, 670 ton (550 – 800 t), and applications in the offshore oil and gas industry, 210 ton (50-390 t). The rest, 200 ton (100-320 t), is related to their application in detergents and maintenance products, personal care products, food additives and medical applications.

In the past, estimates of intentionally produced polymer microplastics or primary microplastics usually only considered microbeads and their application in cosmetics or detergents (for instance (Urbanus et al., 2022; Verschoor and de Valk, 2018)). Here, the full scope of the REACH restriction on intentional microplastics (EC, 2023d) is taken into account. It is clear that, similar to the study by Urbanus et al. (2022), cosmetic and detergent applications only make up a relatively small part of primary microplastic emissions.
Several estimates of the emission of rubber infill exist for the Netherlands. One of the most recent estimates is by Hoeke et al. (2024), reporting a total release for 2100 ton in 2021, which is more than the estimate in this study. The difference can be explained by the 25% higher input of rubber granules in 2021 compared to this study, 14 200 ton and 11 400 t ,respectively, and taking a 36% higher loss rate compared to this study, 0.15 and 0.11, respectively. This loss rate is one of the most uncertain factors.

The overall emission estimate of intentionally produced microplastics is indicative of the size of this source of microplastics in the Netherlands. Therefore, the adopted EU restriction is expected to contribute to the reduction of microplastic release to the environment (see Chapter 4).

3.7 Macroplastics and packaging

About 8600 ton (3800 – 16 000 t) of macroplastics are emitted to the environment. These plastic articles relate to the contributions made by Packaging, textiles and agriculture applications of plastics (Figure 11). These are shown to be major sources that contribute to plastic litter in the environment (Kawecki and Nowack, 2019; Urbanus et al., 2022a). Several other sources may contribute to litter, but it is expected that they contribute less. Nevertheless, it may be relevant to include additional and more refined sources in future work in order to assess the effectiveness of specific mitigation measures, i.e. related to cigarette buds or fireworks.

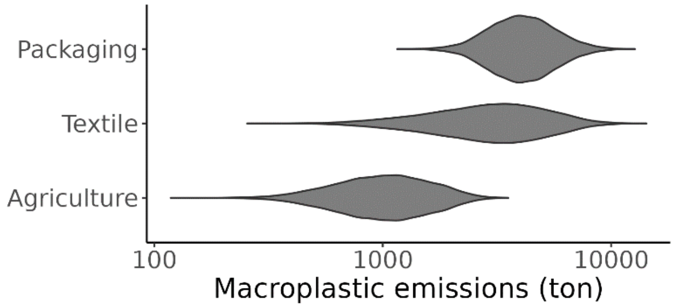


Figure 11 Contribution of packaging, textiles and agriculture to macroplastic emissions to the environment for 2019.

The major contributions from packaging to macroplastic litter is due to items not being cleaned up from on-the-go consumption and subsequent improper discarding of food packaging items. Similarly, improperly discarding textiles and agricultural plastics items that are not subsequently cleaned up make up the majority of litter from those sources.

In a recent report (TNO, 2024) about 14 000 tonnes of packaging plastic is estimated to be lost in the environment in the Netherlands for 2017, which is more than the 95th percentile of our estimate (average 4300 ton) for 2019. We assume the difference does not lie in the amount of packaging used as input. For instance, the reported amount consumed in the TNO study is lower for 2020 (387 000 t) compared to this study (523 000 t). This means there are differences in the transfer coefficients, while other assumptions are made regarding the flows and losses being modelled. Further comparison is only possible after evaluation of the exact modelling details.

In the previous RIVM report (Verschoor and de Valk, 2018) land-based litter fragmentation was reported as the largest potential source of microplastics (~10 000 t) to water alone. Here, the macroplastic emissions to water are estimated to be much lower (248 t) due to updated work on macroplastic losses to water as implemented in recent MFA studies (Kawecki et al., 2018; D. Kawecki and Nowack, 2019; Schwarz et al., 2023). A lot more is emitted to soil (8400 t). It is recommended that further research on this topic includes environmental fate processes. For instance, including transformation of land-based macroplastics to microplastics due to natural fragmentation processes, possibly with a fate model such as SimpleBox4Plastics (Quik et al., 2023) or 'Full Multi River' (Domercq et al., 2022).

Packaging is also a source of 1700 ton (1300 – 2300 t) microplastic emissions to the environment. This is all due to breakup of packaging in the processing of compost to pieces smaller than 1 mm, which end up in the environment through application of compost.

3.8 Polymer types

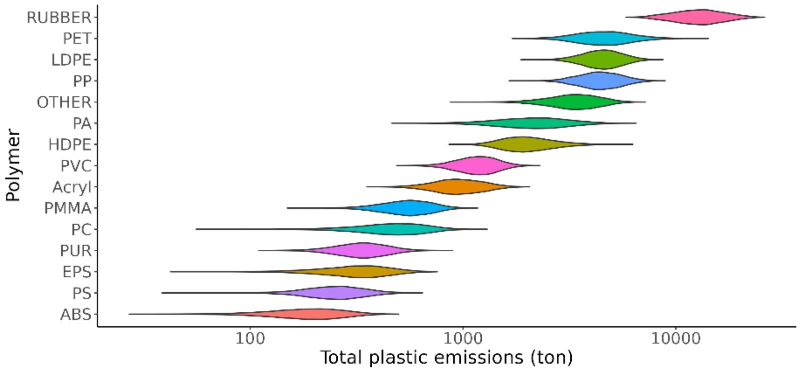


Figure 12 Distribution of polymer types emitted to the environment (soil, water and air) as microplastics for 2019.

Although data on the exact polymers applied in various product categories is scarce, the available data was gathered and applied here, resulting in this distribution of polymer emissions to the environment in the Netherlands (Figure 12).

Although validating these types of assessments by means of Material Flow Analysis is difficult, one approach is to compare the distribution of measured polymers to those measured in the environment. Although not part of this study, it is remarkable that in recent measurements of microplastics in water, sediment and shores of major rivers in the Netherlands, 76% - 86% was PE (HDPE & LDPE) and only 7 – 11% was tyre rubber (SBR) (RWS, 2023). Given that tyre rubber would be the polymer one would expect to find the most on the basis of these results (Appendix D, Figure D1), several aspects need to be considered:

1. Spatial distribution is not accounted for. Some emissions are location-specific. For instance, the majority of tyre wear ends up in the roadside soil.
2. Environmental transformation, transport and degradation processes are not taken into account here, but can play an important role. For instance, the difference in degradation rates between rubber and HDPE/LDPE can affect the degree of accumulation in soil or sediment.
3. The limitations of both the model and field measurements need to be taken into account. For instance by estimating the particle size of the emission estimates and comparing to the size limitations of the field measurements, the minimum and maximum sizes relating to sampling and detection of microplastics. For instance, larger particles from one source or

polymer type are less likely to end up in water than smaller ones from another.

3.9 Comparison to Europe

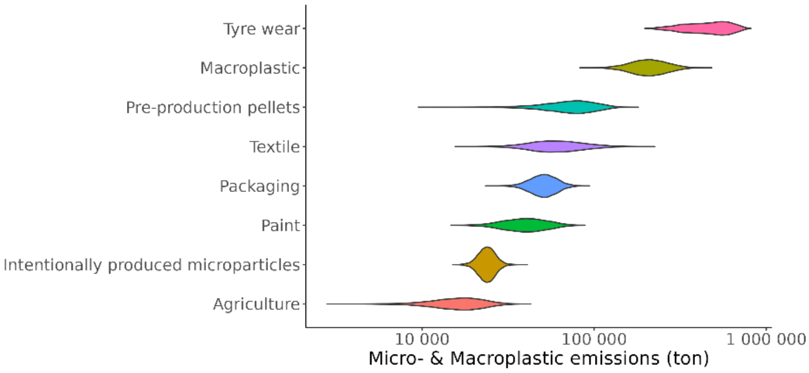


Figure 13 Plastic emissions to the environment for 2019 in the EU-27.

While this study focusses on estimating the emission of microplastics in the Netherlands, most policies are best implemented on a large scale, for instance within the EU as a whole. The same modelling approach was applied to the EU with some input data being scaled to the EU (Tyre wear), but most being available.

The largest three sources of micro- and macroplastic emissions are the same as for the Netherlands, which is to be expected (Figure 13). However, macroplastic emissions are estimated to contribute more than pellets. In comparison to the estimates as part of the EU work on intentional and unintentional releases of microplastics (EC, 2023b, 2023a; ECHA, 2020b), Intentionally produced polymer microplastics, tyre wear and pre-production pellet estimates are similar to the estimates presented here. Overall, the ranking of the various sources is also similar, except for paint and the sources not included in their studies. Paint estimates in this study are a lot lower, even when adopting the same input as was reported in the EC report (EC, 2023a). This points to large differences in estimates of loss rates and other transfer coefficients. Release estimates for textiles in this study are a lot higher, which is probably due to the scope of textiles taken into account, for example not only clothing, but household and technical textiles, too. However, our estimates are screening-level at best, and we recommend further optimisation of the inputs and transfer coefficients.

4 Effect of mitigation measures

Several mitigation measures are ranked in Table 5 on the basis of their overall reduction potential of plastic emissions. The reduction potential is dependent on where in the life cycle or value chain the measure (intervention) is placed, how close to the source of emission it is, and the size of emission per source. It is clear that targeting tyre wear, pre-production pellets and macroplastics is deemed most effective, largely due to those being the largest sources (Figure 7). Out of the top ten mitigation measures (total reduction potential > 1%), four are related to limiting the source through measures that narrow the loop (Table 4). Also, the measure to restrict the use of Intentionally produced polymer microparticles, in this case the only measure implemented using a 100% reduction in 2025, would result in a prioritisation as one of the top mitigation measures as it is also aimed at limiting the source as a narrow-the-loop measure.

Of particular interest is that the top ten also includes four end-of-pipe measures and even two clean-up measures that seem relatively effective. These are clean-up actions aimed at macroplastics in the environment or at tyre wear on the roads. But the most effective measure is treating road runoff at the highway and rural road networks similar to more urban areas in the Netherlands to reduce release of tyre wear. Based on the zero-pollution hierarchy (Figure 2) it is clear that prevention (limiting sources) should be prioritised over minimising or controlling releases (end-of-pipe measures), which in turn should be prioritised over clean-up measures as the costs are usually higher.

Other studies have also pointed towards measures aimed at limiting the source using refuse/redesign mitigation measures as being most effective (Urbanus et al., 2022; Verschoor and de Valk, 2018). The highest potential reduction of emissions to water was estimated for a measure aimed at introducing a legal threshold for tyre abrasion as reported by Verschoor and de Valk (2018). Urbanus et al. (2022) reported the highest reduction of 36% for the measure aimed at reducing plastics consumption. Furthermore, they highlighted 4 more mitigation measures with over 15% effectiveness. Two measures were aimed at reducing macroplastic emissions and use of improved tyres combined with increased capture of tyre wear. These match the top measures as reported on here. They also highlighted a measure aimed at using materials with lower microplastics release potential, which was not considered here, but can be seen as a refuse/redesign measure aimed limiting release at the source.

Although similar to previous studies in some respects, this overview of the effect of mitigations measures fitted to the scope of various policies aimed at various sources is one of the first to include such a broad range of polymer types and microplastics sources, including macroplastics. The modelling approach is now also available for others to perform more refined assessments supporting science-based policies on reducing plastic pollution.

Although this is not a thorough review of all potential mitigation measures, we will discuss the most important results for each source below.

Table 5 Microplastic emission reduction potential ranked based on the overall effect of mitigation measures on microplastic emissions in 2050[a].

ID	Source category	Description of measure	% change compared to source baseline (2030)	% change compared to source baseline (2050)	% change compared to total microplastic emissions baseline (2050)	% change compared to total plastic emissions baseline (2050)
19	Macroplastics[a]	Restrict single/non-essential use to reduce single use plastic consumption	-28	-30	Not quantified	-11
5	Tyre wear	Capture road runoff at highway and rural road networks	-30	-35	-14	-11
4	Tyre wear	Lower wear of tyres	-28	-31	-13	-10
22	Macroplastics[a]	Clean up in the environment	-20	-21	Not quantified	-6.0
2	Pre-production pellets	Reduce pellet loss industrial plants	-15	-18	-5.5	-4.4
14	Technical textiles	Adjust percentage of plastic in technical textiles or limit use	-26	-30	-2.6	-4.3
16	Technical textiles	Improve maintenance in order to reduce in use releases	-34	-39	-3.5	-4.3
6	Tyre wear	Improved road cleaning	~0[c]	-12	-4.7	-3.8
1	Pre-production pellets	Prevent spillage transport (better packaging, improved storage)	-14	-14	-4.3	-3.4
18	Agriculture	Promote eco-friendly materials (bio-plastics)/only essential use of plastics	-29	-31	-0.88	-1.6
15	Technical textiles (macro)	Stimulate recovery and recycling at end of life	~0[c]	-3.2	Not quantified	-0.60
7	Paint	New types of paint (less plastic) / reduce paint use	-16	-27	-0.61	-0.48
3	Pre-production pellets	Clean-up of water flow coming out of industrial plants	~0[c]	~0[c]	-0.55	-0.44
11	Clothing + home textiles	Less plastic in textiles (more natural materials)	-24	-28	-0.40	-0.39

ID	Source category	Description of measure	% change compared to source baseline (2030)	% change compared to source baseline (2050)	% change compared to total microplastic emissions baseline (2050)	% change compared to total plastic emissions baseline (2050)
10	Paint	Better recovery EOL paint	-20	-18	-0.41	-0.33
17	Agriculture	Encourage reuse and recovery	-2.6	-6.0	-0.17	-0.30
21	Pre-production pellets	Capture MPs at recycling plants (end of pipe)	~0[c]	~0[c]	~0[c]	-0.30
13	Clothing + home textiles	Reduce emissions to wastewater	-26	-24	-0.33	-0.26
9	Paint	Reduce losses at time of application, due to rinsing etc.	~0[c]	~0[c]	~0[c]	~0[c]
23	Intent. prod. microplastics[b]	Restrict use as aimed for by ECHA restriction	-90	-100	-7.0	-5.6

The emission reduction potential per source category is also provided (independent of the overall contribution to emissions). Measures 19,20 and 22 on macroplastics are relative total plastic emissions (micro + macro).

a. Overall emission change of macroplastics measures are calculated relative to total plastic emissions, other measures only related to total microplastic emissions.

b. Included as implemented for 100% in 2025, only for comparison. Derogation periods etc. not accounted for.

c. Change is within margin of numerical error. This is 2.5% when comparing sources separately and 0.12% when comparing tot total (micro-) plastics emissions.

4.1 Pre-production pellets

Out of the four measures aimed at reducing pre-production pellet releases, the end-of-pipe measure aimed at industrial plants shows the higher overall effect, followed by the end-of-pipe measure aimed at reducing losses during transport. The two other measures had a much more specific scope and thus a score lower in effect. One aimed at improving water treatment from industrial plants has a small effect (<1%) because most of the releases are estimated to go directly to soil. Also, the measure aimed at reducing emissions specifically focussed on losses at recycling plants has a small effect (<1%) on total pellet releases as this source of pellets is itself small.

For the recent proposal for regulating pellet losses in the EU, several policy options were evaluated (EC, 2023b). Out of these options, the mandatory requirement to prevent and reduce pellet losses in a new European law was highlighted as resulting in the highest reduction of pellet releases to the environment. This seems to be in line with a relatively high effect of reducing pellet losses at industrial plants (Measure 2). Other options selected in the EU study (EC, 2023b) are to improve packaging and to set an EU emissions target, which is to be combined with a mandatory standardised methodology to measure pellet losses. The reduction of pellet releases due to the improved packaging policy measure was not reported, and it is unclear how, exactly, this would affect a reduction in spillage. Nonetheless, preventing spillage during transport (Measure 1) ranks ninth in the potential to reduce microplastic emissions to the environment as quantified in this study. It should be noted that further refinement of our assessment is advised, as there is considerable uncertainty in the loss coefficients applied, and this estimate does not include a degree of feasibility.

4.2 Tyre wear

The results here show that all three quantified measures have a relatively high effect on reducing overall microplastic emissions to the environment from tyre wear. Each measure has a different place in the zero-pollution hierarchy (Table 4). As such, these measures range from more local actions aimed at reducing release due to untreated road run-off (Measure 5) and improved street cleaning (Measure 6) to lowering overall tyre wear release (Measure 4), which would require implementation at a much larger scale.

Reducing the emissions of tyre wear to the environment is the subject of several studies, both completed (Gehrke et al., 2023; Verschoor and de Valk, 2018) and ongoing (Hoeke, 2024; LEON-T project, 2024), several of which study a much more detailed set of mitigation measures. It goes too far to summarise all of them here. An important outcome of those studies and our assessment is that policy actions should be aimed at a range of measures that, together, could have a significant effect on reducing tyre wear emissions. For instance, tyre wear is related to driver behaviour, tyre quality and pressure, vehicle suspension and road characteristics, meaning that all these aspects could be optimised to realise tyre wear reduction.

Given the zero-pollution hierarchy, a quick solution could be to invest in street cleaning, but the preferred solution would be to limit tyre wear in the first place. The applied modelling approach here is well suited to be further refined for studying the effect of mitigation measures aimed at end-of-pipe measures or clean-up of tyre wear. However, measures aimed at lowering the wear of tyres require the inclusion of more mechanisms relating to wear itself, such as tyre interaction with the road and driver behaviour. This is, for instance, part of the work being conducted in other projects (LEON-T project, 2024).

4.3 Paints and coatings

Reducing the release of microplastics from paints and coatings is quantified here on the basis of two strategies, similarly implemented for clothing and household textiles, which is based on (i) narrowing the loop by limiting sources, and (ii) closing the loop by reducing leakage to the environment. The measure focussed on limiting the source has the highest effect (Measure 7).The measure aimed at improved recovery of paint residues at end of life (Measure 10) also indicates a positive effect. However, the measure aimed at reducing losses at time of paint application (Measure 9), due to rinsing etcetera, shows no effect, given the model uncertainty. The effect is so small (< 1 t/a) because it only affects do-it-yourself water-based paints. Our selection of measures also included application of higher-quality products with increased lifetimes (Measures 8, 12 and 20), but these were not quantified.

The measure relating to limiting the source could, for instance, be due to new paints with a lower polymer content or a reduction of the amount of paint needed. Such developments would preferably be addressed on a large scale, EU or global, but can also be part of local sustainable procurement efforts. Limiting leakage to the environment could potentially be addressed nationally as a lot of losses come from the end-of-life phase (Measure 10), for instance due to sanding. Previous studies (Verschoor and de Valk, 2018) already suggested replacing older sanders as a measure.

4.4 Textiles

A total of five mitigation measures were assessed for textiles. Clothing and home textiles were combined in the analysis, while technical textiles were assessed separately.

The higher ranking of measures aimed at technical textiles compared to measures aimed at clothing or home textiles is in line with the higher emissions from technical textiles compared to the other two (Figure 10). The measure aimed at reducing in-use release (Measure 16) and limiting the use of technical textiles (Measure 14) have a relatively high overall effect. This is in line with the expectation that in-use emissions play an important role in reducing microplastic emissions. End-of-life emissions mainly take the form of macroplastics (Measure 15), and as such, they do not lead to a reduction in emissions of microplastics compared to the baseline.

The measures aimed at clothing and home textiles all rank outside the top ten. However, these measures do have an effect in reducing microplastics from this specific source (see the reduction percentages relative to the source in Table 5). Measures to reduce emissions due to fewer polymers being used in clothing and home textiles rank highest of the measures (Measure 11), followed by reducing emissions to waste water (Measure 13), for example due to filtering microplastics during washing.

4.5 Agriculture

Transitioning in agriculture towards using less plastics (Measure 18) ranks tenth compared to the other measures contributing towards total plastic emissions reduction. The end-of-pipe measure aimed at reducing losses due to increased collection and recycling or reuse (Measure 17) has a relatively small effect on reducing microplastic emissions compared to most other measures. This is similar to the end-of-pipe measure for clothing and home textiles (Measure 13) and for paint (Measure 10). However, those measures for paint and textiles show much higher reduction potential relative to the source compared to this type of measure for agriculture. This is due to the relatively high emissions during use.

4.6 Intentionally produced polymer microparticles

The effect of the ban in application of intentionally produced polymer microparticles was implemented as a 100% stop of use in 2025. By 2030, the effect of this measure is not yet 100% due to the lifetime of artificial pitches not being end-of-life. By 2050, it is assumed producers would have all transitioned to using different materials, resulting in realising the full potential, no emissions due to this source. This was not refined according to the specification of the ECHA restriction which has several transition terms for various types of applications. This could be implemented in future research. Also, it would be interesting to see if the alternative productions would contribute to the unintentional release of plastics.

4.7 Macroplastics

Reducing macroplastic release to the environment is an effective approach to reducing total plastic emissions to the environment. Specifically when restricting the consumption of these types of plastics, or switching to biodegradable or non-polymer variants (Measure 19), it should be noted that this was applied to all sub-categories of products at once, for instance agricultural pipes and on-the-go packaging. Agricultural pipes have a much longer lifetime and a different function than on-the-go packaging, which is emitted shortly after being consumed. Further research could specify this type of measure more precisely, for instance also quantifying effects of the implementation of the single-use Plastics directive.
Increasing the lifetime of such plastic applications is a relevant measure, but was not quantified in this study as it requires more data on the effect this has on reduced consumption in the years after introducing a longer-lifetime product.

A well-known measure for macroplastics is clean-up in the environment (Measure 22), which ranks fourth when considering the potential reduction in total plastic emissions. It should be clear from the non-pollution hierarchy that clean-up is usually a last resort, but for macroplastics, this can still make sense compared to microplastics, which are much harder to clean up after they are present in the environment, or after macroplastics have degraded to microplastics. It should be noted, however, that the emissions do not directly take the form of microplastics, but should be seen as potential microplastics after fragmentation. Further research is needed on quantification of the process of fragmentation.

Overall, the effect of mitigating emissions of macroplastics is calculated as relatively high, as it is a large source of microplastics. Also, several other mitigation measures have an effect on macroplastic emissions, such as those aimed at textiles and agriculture. For instance, increasing the fraction of technical textiles going to recycling (Measure 15) only affects total (macro-) plastic emissions. This is also an example of a case where a measure could increase the emissions of microplastics. In the case of increased recycling, this could mean increased emission of pre-production pellets at the recycling plant. But trade-offs also extend much wider in terms of other emissions, such as greenhouse gas emissions. This means that in estimating the effectiveness of mitigation measures, a model system as applied here could inform trade-offs between various plastic emissions. Other approaches, such as Life Cycle Assessments and Cost Benefit Analysis, could inform trade-offs covering a much broader set of impacts, preferably including those of plastics. Work on including the impact of macroplastics and microplastics in LCA is ongoing, see e.g. (Schwarz et al., 2024). This is particularly relevant to consider with regard to alternatives to plastics being applied, for example the impact of biological materials versus synthetic polymers.

5 Conclusions and recommendations

RIVM developed a harmonized and open access model, that uses a material flow approach, to calculate microplastic emissions into the environment from various sources. Next, an inventory of mitigation measures was made from literature and a stakeholder workshop. The model was then also used to calculate a first reduction potential of a selection of measures.

The emission estimates show that tyre wear, pre-production pellets and macroplastics are the largest sources of plastics in the environment. The mitigation measures aimed at these sources also contribute the most to reducing plastic emissions to the environment.

As such, the top ten mitigation measures ranked from most to least reduction in plastic emissions are:

- Restrict macroplastic consumption (for instance by reducing single-use plastics or alternative materials);
- Increase treatment of tyre wear in road runoff, specifically outside of urban areas;
- Lower the wear of tyres;
- Clean up macroplastics in the environment;
- Reduce pellet loss at industrial plants;
- Reduce polymer use in technical textiles;
- Improve maintenance of technical textiles in order to reduce in-use releases;
- Improve road cleaning to capture tyre wear;
- Prevent spillage of pellets during transport;
- Reduce polymer-based material use in agriculture, for instance only essential use of plastics.

These mitigation measures were all put forward by stakeholders and experts, selected on the basis of a solution-focussed approach. RIVM then used this measures to calculate the reduction potential, which is dependent on the type of measure, e.g. narrowing or closing the loop. This assessment of the emission reduction potential of each measure enabled us to rank these measures on the basis of a generic efficiency and implementation level (30%).

It is advisable that – in line with the solution-focussed assessment approach – the modelling results are used for refining the measures and discussing their efficiency and feasibility in practice. This would allow for a more absolute emission reduction that each measure can have, for instance not using the generic 30% reduction applied here, but a more realistic value and may give an updated order of ranking. This will most likely result in refinement of the mitigation measures, too, as the actions that can lead to such measures differ, for instance implementing a tyre wear limit versus implementing a tyre pressure monitoring system, both aimed at lowering tyre wear.

Furthermore, the analysis clearly shows that various measure types aimed at narrowing the loop and closing the loop can all be effective, but require different implementations at different spatial, geographical and economical scales. This should be part of further refinement of studies including a quantified degree of feasibility of each mitigation measure. Also, trade-offs outside of the scope of plastic emissions (e.g. other effects such as greenhouse gas emissions) are relevant to consider in decisions on the implementation of mitigation measures.

The modelling approach applied here provided for the first time such a broad overview of the major sources of microplastics and the effect mitigation measures can have on reducing the emissions. The applied model is flexible in its application and can support a wide range of studies, such as on the transition towards (more) circular application of plastics or support risk assessment of microplastics, which is relevant for policymakers working on reducing plastic pollution.

RIVM recommends that:
Mitigation measures should be compared based on an estimate of:

- The technical efficiency of the measure,
- The feasibility of implementation in practice and
- The type of regulatory implementation per (refined) mitigation measure.

For instance a specific source of interest can be selected, and together with relevant stakeholders and experts, the above can be refined to get an absolute estimate of the emission reduction.

The environmental fate of microplastics should be included, which is necessary to assess exposure and assist in environmental monitoring of microplastics. This is possible by using existing fate models, such as SimpleBox4Plastics. Combining both emissions and fate is necessary to better understand effects of microplastics on human and environmental health.

Develop the current model by:

- Reducing uncertainty of the estimates and implementing more refined transfer coefficients, for instance temporal, regional, or activity-specific loss rates. This can be done, for instance for emissions related to losses at industrial plants and emissions during transport of pre-production pellets.
- Include quantification of the emission reduction due to changes in lifetime of products. This will also allow to reflect on effects due to, for instance, re-use.
- Further optimising the model design to decrease computation time, as applying the model probabilistically and dynamically in time is computationally intensive. The model is made available open access for use by experts, which provides additional opportunities for further model development.

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7 Acknowledgements

We would like to thank Anna Schwarz, Sietske Lensen and Sieger Henke from TNO for their valuable discussions and contributions during the project, specifically in relation to the Textiles and Agriculture product groups.

8 Appendix A – source data

8.1 Overview

All the input data and transfer coefficients are available from https://doi.org/10.5281/zenodo.12636554.

Depending on the availability of data, input values were filled out per category for certain years (Table A1).

Table A1 Overview of product categories and years for which input data was available.

Product sector	**Years (NL)**	**Years (EU)**
Agriculture	2018-2019	2018-2019
Clothing	2019	2017
Domestic primary plastic production	1995-2020	2003-2020
Import of primary plastics	1995-2020	2003-2020
Household textiles	2017	2017
Intentionally produced microparticles	2020	2020
Packaging	2017-2020	2017-2020
Paint	2015-2022	2019
Technical textiles	2017	2017
Tyre wear	1990, 1995, 2000, 2005, 2010, 2015, 2019, 2020	1990, 1995, 2000, 2005, 2010, 2015, 2019, 2020

8.2 Pre-production pellets

Raw plastic materials can come in the form of i.e. pellets, flakes, powders or liquids. In this report, the term “pre-production pellets” will be used to refer to all forms of raw plastic materials.

Pre-production pellets are raw plastic materials that are used to manufacture plastic products. These pellets are heated to create plastic products which do not contain microplastics themselves. Pellets are unintentionally lost to the environment during production, storage, transportation (including loading/unloading) and manufacturing of plastic products (Lassen et al., 2015). There is an opportunity for pellet loss whenever pellets are handled. Examples are breaking of weak packaging, loading/unloading a vehicle, a container lost at sea or pellets are blown away from outside storage bins (Cole and Sherrington, 2016). To calculate the amount of plastic pellets used in the Netherlands and the EU, not only the domestic production but also the import and export of plastic pellets was taken into account. An overview of the relationship between the production, import/export and other compartments is presented in Figure A1.

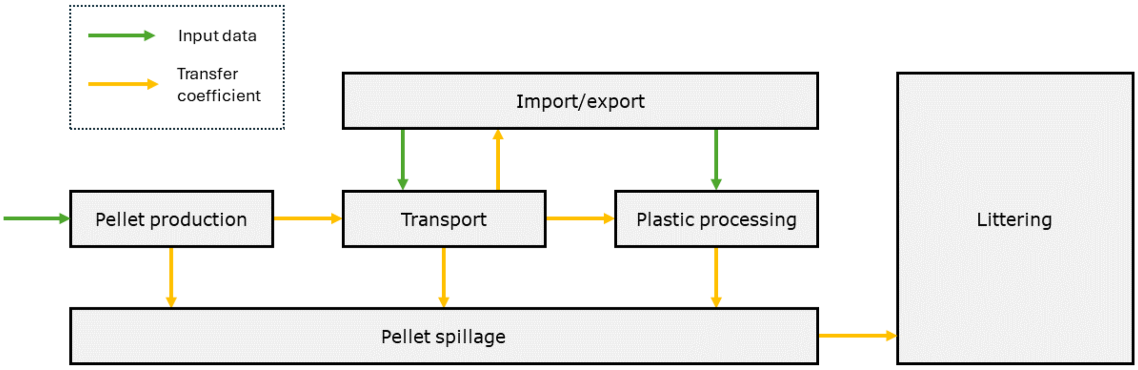


Figure A1 Flow diagram depicting compartments and flows for pre-production pellets.

8.2.1 *Netherlands scale input data*

Information on the domestic primary plastic production, import and export for the years 1995 to 2021 were obtained from Eurostat ("Statistics | Eurostat," n.d.). This dataset contained information on nearly all polymer types included in the model (LDPE, HDPE, PP, PS, EPS, PVC, PET, ABS, PC, PMMA, PA, PUR and OTHER). Data was obtained from Eurostat using PRODCOM codes. These codes each represent a type of good. In this research, only virgin primary plastic microplastics were taken into account. The PRODCOM categories chosen were compared to those used in another recent research on microplastic emissions from pre-production pellets (EC, 2023b). Three categories were not used in this research but used in the research by the European Commission. These categories were not included for two reasons: (1) the categories do not specifically pertain to microplastics, but also to sheets of primary plastics; (2) recycled plastics are included in one of the categories. In 2019, the total pre-production pellet input was 11292 kt (Table A2).

8.2.2 *European Union scale input data*

Information on the plastic production, import and export from 2003 to 2021 in the European Union was obtained from Eurostat ("Statistics | Eurostat," n.d.). The same PRODCOM codes were used to gather input data from Eurostat. In 2019, the total pre-production pellet input was 75907 kt (Table A2).

Because the chosen PRODCOM categories are different from the EC (2023) report, the total input mass op pre-production pellets for 2019 is different, too. EC estimated that about 65.3 million tons of pellets were produced in the EU and that 12.7 million tonnes were imported. When using the categories selected in this study, given in Table A3, 65.5 million tonnes of pellets were produced in the EU in 2019, and 10.4 million tonnes were imported.

Table A2 Input data for 2019 summed over all polymers in kt.

	NL	EU
Domestic production	7 425	65 513
Import	3 867	10 394
Total pre-production pellets	11 292	75 907

Table A3 PRODCOM codes and descriptions of polymers in primary forms.

Prodcom code	Prodcom name	Polymer
20.16.10.35	Linear polyethylene having a specific gravity < 0,94, in primary forms	LDPE
20.16.10.39[a]	Polyethylene having a specific gravity < 0,94, in primary forms (excluding linear)	LDPE
20.16.10.50	Polyethylene having a specific gravity of >= 0,94, in primary forms	HDPE
20.16.10.70	Ethylene-vinyl acetate copolymers, in primary forms	OTHER
20.16.10.90	Polymers of ethylene, in primary forms (excluding polyethylene, ethylene-vinyl acetate copolymers)	OTHER
20.16.51.30	Polypropylene, in primary forms	PP
20.16.51.50	Polymers of propylene or of other olefins, in primary forms (excluding polypropylene)	OTHER
20.16.20.35	Expansible polystyrene, in primary forms	EPS
20.16.20.39	Polystyrene, in primary forms (excluding expansible polystyrene)	PS
20.16.20.50	Styrene-acrylonitrile (SAN) copolymers, in primary forms	OTHER
20.16.20.70	Acrylonitrile-butadiene-styrene (ABS) copolymers, in primary forms	ABS
20.16.20.90	Polymers of styrene, in primary forms (excluding polystyrene, styrene-acrylonitrile (SAN) copolymers, acrylonitrile-butadiene-styrene (ABS) copolymers)	OTHER
20.16.30.10	Polyvinyl chloride, not mixed with any other substances, in primary forms	PVC
20.16.30.23	Non-plasticised polyvinyl chloride mixed with any other substance, in primary forms	PVC
20.16.30.25	Plasticised polyvinyl chloride mixed with any other substance, in primary forms	PVC
20.16.30.40	Vinyl chloride-vinyl acetate copolymers and other vinyl chloride copolymers, in primary forms	OTHER
20.16.30.90	Polymers of halogenated olefins, in primary forms, n.e.c.	OTHER
20.16.30.60[a]	Fluoropolymers	OTHER
20.16.52.30[a]	Polymers of vinyl acetate, in aqueous dispersion, in primary forms	OTHER
20.16.52.50	Polymers of vinyl acetate, in primary forms (excluding in aqueous dispersion)	OTHER
20.16.52.70	Polymers of vinyl esters or other vinyl polymers, in primary forms (excluding vinyl acetate)	OTHER
20.16.53.50	Polymethyl methacrylate, in primary forms	PMMA
20.16.53.90	Acrylic polymers, in primary forms (excluding polymethyl methacrylate)	PMMA
20.16.40.13	Polyacetals, in primary forms	OTHER

Prodcom code	Prodcom name	Polymer
20.16.40.15	Polyethylene glycols and other polyether alcohols, in primary forms	OTHER
20.16.40.20	Polyethers, in primary forms (excluding polyacetals, polyether alcohols)	OTHER
20.16.40.30[a]	Epoxide resins, in primary forms	OTHER
20.16.40.40	Polycarbonates, in primary forms	PC
20.16.40.50[a]	Alkyd resins, in primary forms	OTHER
20.16.40.62	Polyethylene terephthalate in primary forms having a viscosity number of >= 78 ml/g	PET
20.16.40.64	Other polyethylene terephthalate in primary forms	PET
20.16.40.90	Polyesters, in primary forms (excluding polyacetals, polyethers, epoxide resins, polycarbonates, alkyd resins, polyethylene terephthalate, other unsaturated polyesters)	OTHER
20.16.40.70[a]	Unsaturated liquid polyesters, in primary forms (excluding polyacetals, polyethers, epoxide resins, polycarbonates, alkyd resins, polyethylene terephthalate)	OTHER
20.16.40.80	Unsaturated polyesters, in primary forms (excluding liquid polyesters, polyacetals, polyethers, epoxide resins, polycarbonates, alkyd resins, polyethylene terephthalate)	OTHER
20.16.54.50	Polyamide -6, -11, -12, -6,6, -6,9, -6,10 or -6,12, in primary forms	PA
20.16.54.90	Polyamides, in primary forms (excluding polyamide -6, -11, -12, -6,6, -6,9, -6,10 or -6,12)	PA
20.16.56.50	Phenolic resins, in primary forms	OTHER
20.16.56.70	Polyurethanes, in primary forms	PUR
20.16.59.20	Petroleum resins, coumarone-indene resins, polyterpenes, polysulphides, polysulphones, etc., n.e.c., in primary forms	OTHER
20.16.59.60[b]	Natural and modified natural polymers, in primary forms (including alginic acid, hardened proteins, chemical derivatives of natural rubber)	RUBBER
22.19.10.00[b]	Reclaimed rubber in primary forms or in plates, sheets, or strips	RUBBER
22.19.20.19[b]	Other compounded rubber, unvulcanised, in primary forms or in plates, sheets or strip	RUBBER

[a]: Included in this research, not included in EC, 2023, [b]: Not included in this research, included in EC, 2023.

8.2.3 *Transfer coefficients*

Based on the input data, the fractions for export for each year and material was calculated using the following equation: $f_{export} = M_{export} \div (M_{export} + M_{used})$. The fractions for domestic use of pellets were calculated as $f_{used} = 1 - f_{export}$.

Transfer coefficients for pellet losses at industrial plants were calculated by using information from Eunomia (Cole and Sherrington, 2016; Sherrington et al., 2016). They estimate that the lower limit of pellet loss during processing of pre-production pellets is 0.0001%. This lower limit was used for both loss during transport of pellets and during production/conversion of pellets at industrial plants. The upper limits of pellet loss during transport and at industrial plants was defined as 0.05% and 0.04% respectively. The model includes a range of compartments for losses during transport on land and losses at sea. Lassen et al. (2015) reported that in Norway, 250 t/y is lost to the environment during transport. Of this 250 t/y, 22 t/y is lost at sea. This means that 8.8% of the pellets lost during transport is lost at sea, and 91.2% of the pellets is lost during transport on land. These percentages were used to calculate the upper limits of pellet loss during transport on land and sea. These transfer coefficients are assumed to be the same for the Netherlands and the EU.

TCs for transfer to other compartments were obtained from various sources. The compartments, transfer coefficients and their sources can be found in Table A4.

Table A4 Transfer coefficients.

From	To	Scale	Material	Value	Source
Domestic primary plastic production	Transport of primary plastics	any	any	rest	
Import of primary plastics	Transport of primary plastics	any	any	1.00E+00	
Transport of primary plastics	Pellet conversion	any	any	rest	
Transport of primary plastics	Pellet losses transport land	any	any	1.00E-06	Sherrington et al. (2016)
Transport of primary plastics	Pellet losses transport land	any	any	4.56E-04	Lassen et al. (2015), Sherrington et al. (2016)
Transport of primary plastics	Sea water (micro)	any	any	1.00E-06	Sherrington et al. (2016)
Transport of primary plastics	Sea water (micro)	any	any	4.40E-05	Lassen et al. (2015), Sherrington et al. (2016)
Pellet losses transport land	Surface water (micro)	any	any	2.50E-01	Cole and Sherrington (2016)
Pellet losses transport land	Residential soil (micro)	any	any	7.50E-01	Cole and Sherrington (2016)
Pellet conversion	Plastic products	any	any	rest	
Domestic primary plastic production	Pellet losses industrial plants	any	any	1.00E-06	Sherrington et al. (2016)
Domestic primary plastic production	Pellet losses industrial plants	any	any	4.00E-04	Sherrington et al. (2016)
Pellet losses industrial plants	Industrial stormwater (micro)	any	any	4.00E-03	Cole and Sherrington (2016)

From	To	Scale	Material	Value	Source
Pellet losses industrial plants	Residential soil (micro)	any	any	9.96E-01	Cole and Sherrington (2016)
Pellet conversion	Pellet losses industrial plants	any	any	1.00E-06	Sherrington et al. (2016)
Pellet conversion	Pellet losses industrial plants	any	any	4.00E-04	Sherrington et al. (2016)
Transport of primary plastics	Export of primary plastics	NL	LDPE	8.94E-01	Statistics | Eurostat (n.d.)
Transport of primary plastics	Export of primary plastics	NL	HDPE	8.45E-01	Statistics | Eurostat (n.d.)
Transport of primary plastics	Export of primary plastics	NL	PP	2.16E-01	Statistics | Eurostat (n.d.)
Transport of primary plastics	Export of primary plastics	NL	PS	1.48E-01	Statistics | Eurostat (n.d.)
Transport of primary plastics	Export of primary plastics	NL	EPS	6.66E-01	Statistics | Eurostat (n.d.)
Transport of primary plastics	Export of primary plastics	NL	PVC	8.50E-01	Statistics | Eurostat (n.d.)
Transport of primary plastics	Export of primary plastics	NL	PET	1.00E+00	Statistics | Eurostat (n.d.)
Transport of primary plastics	Export of primary plastics	NL	ABS	1.00E+00	Statistics | Eurostat (n.d.)
Transport of primary plastics	Export of primary plastics	NL	PC	4.32E-01	Statistics | Eurostat (n.d.)
Transport of primary plastics	Export of primary plastics	NL	PMMA	6.70E-01	Statistics | Eurostat (n.d.)
Transport of primary plastics	Export of primary plastics	NL	PA	1.00E+00	Statistics | Eurostat (n.d.)
Transport of primary plastics	Export of primary plastics	NL	PUR	6.74E-01	Statistics | Eurostat (n.d.)
Transport of primary plastics	Export of primary plastics	NL	OTHER	1.00E+00	Statistics | Eurostat (n.d.)
Transport of primary plastics	Export of primary plastics	EU	LDPE	1.57E-01	Statistics | Eurostat (n.d.)

From	To	Scale	Material	Value	Source
Transport of primary plastics	Export of primary plastics	EU	HDPE	1.69E-01	Statistics | Eurostat (n.d.)
Transport of primary plastics	Export of primary plastics	EU	PP	9.96E-02	Statistics | Eurostat (n.d.)
Transport of primary plastics	Export of primary plastics	EU	PS	1.63E-01	Statistics | Eurostat (n.d.)
Transport of primary plastics	Export of primary plastics	EU	EPS	4.97E-02	Statistics | Eurostat (n.d.)
Transport of primary plastics	Export of primary plastics	EU	PVC	2.26E-01	Statistics | Eurostat (n.d.)
Transport of primary plastics	Export of primary plastics	EU	PET	9.56E-02	Statistics | Eurostat (n.d.)
Transport of primary plastics	Export of primary plastics	EU	ABS	2.45E-01	Statistics | Eurostat (n.d.)
Transport of primary plastics	Export of primary plastics	EU	PC	2.00E-01	Statistics | Eurostat (n.d.)
Transport of primary plastics	Export of primary plastics	EU	PMMA	3.14E-01	Statistics | Eurostat (n.d.)
Transport of primary plastics	Export of primary plastics	EU	PA	2.37E-01	Statistics | Eurostat (n.d.)
Transport of primary plastics	Export of primary plastics	EU	PUR	1.66E-01	Statistics | Eurostat (n.d.)
Transport of primary plastics	Export of primary plastics	EU	OTHER	3.46E-01	Statistics | Eurostat (n.d.)

8.3 Tyre wear

Tyre wear is estimated based on the existing approach applied by the Emission registry in the Netherlands (RWS, 2022). This means that the data for Europe is based on the emission factors derived for the Netherlands using the method by (Geilenkirchen et al., 2023). As such the starting point of the MFA model is the released tyre wear (input in kiloton) which then follows the different routes to the environment (direct to air, direct to road-side soil and through run-off to road-side soil and water) following mainly the study by Hoeke et al. (2024) and Sieber et al. (2020). Releases from tyre crumb used as infill are also estimated as part of intentionally produce polymer microparticles (see above), other applications of tyre rubber material are not included in this analysis (e.g. agricultural mats or rubber tiles). Inputs are reported in Table A7. TCs are reported in Table A8.

8.3.1 *Estimate of Rubber input due to Tyre wear*

Tyre wear consists of the rubber fraction of Tyres that is release due to friction with the road surface. Although Tyre Rubber is not a homogeneous material and consists of two important types: Natural Rubber and Styrene Butadiene Rubber, we do not distinguish these here.

Tyre wear due to friction with the road is dependent on tyre characteristics, vehicle characteristics, road characteristics and driver behaviour. Different approaches are available to estimate tyre wear e.g. based on emission factors or tyre sales. Here we choose the standard method derived for the Netherlands as part of the National emissions registry (Geilenkirchen et al., 2023). This method uses emission factors (Table A5) derived for different vehicle categories and three types of road networks (Urban, Rural and Highway). Six vehicle categories are considered here: Passenger cars, Motorcycles, Mopeds, Delivery vans, Lorries and Busses. As only single ‘average’ emission factors are reported in Geilenkirchen et al. (2023) we included the variability as found by the ADAC for passenger vehicle tyres (ADAC, 2022). New low and high emission factors were calculated using a 57% - 166% variability found relative to the average emission factor reported for the range of tyres tested by the ADAC. Thes factors were applied to the emission factors for all vehicle categories.

The total release of tyre wear particles (TWP) is based on multiplying the total distance driven per year per vehicle (Table A6) and road type with the respective emission factor for the Netherlands. This is added up to the total tyre wear released (Table A31). The distances driven per vehicle type are not available for the whole of Europe. For this reason a rough approximation of tyre wear at the EU scale is estimated based on the ratio in population size between the Netherlands and the whole of Europe. This can be improved if distance data becomes available.

Table A5 Emission factors (mg/km) applied for different vehicle and road types in the Netherlands. Written as low estimate-high estimate.

Type of vehicle	***Urban (mg/km)***	***Rural (mg/km)***	***Highway (mg/km)***
Passenger cars	92-169	59-109	73-134
Motorcycles	42-77	27-50	33-60
Mopeds	9-17	6-50	7-60
Delivery vans	111-204	71-131	87-161
Lorries	593-1091	381-701	466-858
Busses	289-533	186-343	227-419

Values from Geilenkirchen et al. (2023) were multiplied with high and low factors from ADAC (2022). Source:(ADAC, 2022; Geilenkirchen et al., 2023).

Table A6 Distances (km) driven in the Netherlands per Vehicle and Road type Source: CBS data as reported in (RWS, 2022).

Year	***Road type***	***Passenger cars***	***Motorcycles***	***Moped***	***Delivery van***	***Lorries***	***Busses***
1990	Bebouwde kom	23214	136	1196	3987	1144	683
1995	Bebouwde kom	21173	245	930	3462	1085	712
2000	Bebouwde kom	18679	318	1032	2458	886	655
2005	Bebouwde kom	20166	372	1150	2821	800	640
2010	Bebouwde kom	20814	393	1513	2739	751	691
2015	Bebouwde kom	21485	370	1597	2691	697	692
2019	Bebouwde kom	22851	384	1691	3007	729	716
2020	Bebouwde kom	22851	384	1663	3007	729	716
1990	Landelijke wegen	30498	369	512	2445	1710	399
1995	Landelijke wegen	30408	665	400	3281	1656	413
2000	Landelijke wegen	32633	863	455	4914	1474	411
2005	Landelijke wegen	35199	1008	515	5635	1459	390
2010	Landelijke wegen	36221	1066	677	5452	1492	406
2015	Landelijke wegen	37303	1004	712	5347	1480	399
2019	Landelijke wegen	39453	1046	748	5945	1583	422
2020	Landelijke wegen	39453	1044	735	5945	1583	422
1990	Autosnelwegen	28157	383	0	1635	2945	160
1995	Autosnelwegen	32572	699	0	3820	3891	163
2000	Autosnelwegen	41887	909	0	7982	4760	191
2005	Autosnelwegen	44973	1070	0	9148	4859	172
2010	Autosnelwegen	45291	1140	0	8828	5038	165
2015	Autosnelwegen	46301	1062	0	8642	5048	155
2019	Autosnelwegen	47881	1098	0	9601	5405	172
2020	Autosnelwegen	47881	1098	0	9601	5405	172

Table A7 Total tyre wear input (kton) per year for the Netherlands (NL) and Europe (EU-27).

COMPARTMENT	**YEAR**	**SCALE**	**MATERIAL**	**RELEASE (KT)**	**SOURCE**
TYRE WEAR	1990	NL	Rubber	14.05	Calculation based on (RWS, 2022)
TYRE WEAR	1995	NL	Rubber	15.10	Calculation based on (RWS, 2022)
TYRE WEAR	2000	NL	Rubber	16.78	Calculation based on (RWS, 2022)
TYRE WEAR	2005	NL	Rubber	17.78	Calculation based on (RWS, 2022)

COMPARTMENT	YEAR	SCALE	MATERIAL	RELEASE (KT)	SOURCE
TYRE WEAR	2010	NL	Rubber	18.04	Calculation based on (RWS, 2022)
TYRE WEAR	2015	NL	Rubber	18.23	Calculation based on (RWS, 2022)
TYRE WEAR	2019	NL	Rubber	19.34	Calculation based on (RWS, 2022)
TYRE WEAR	2020	NL	Rubber	19.34	Calculation based on (RWS, 2022)
TYRE WEAR	1990	EU	Rubber	393.48	Scaling from NL to EU using population
TYRE WEAR	1995	EU	Rubber	414.54	Scaling from NL to EU using population
TYRE WEAR	2000	EU	Rubber	451.94	Scaling from NL to EU using population
TYRE WEAR	2005	EU	Rubber	473.98	Scaling from NL to EU using population
TYRE WEAR	2010	EU	Rubber	478.95	Scaling from NL to EU using population
TYRE WEAR	2015	EU	Rubber	478.09	Scaling from NL to EU using population
TYRE WEAR	2019	EU	Rubber	498.41	Scaling from NL to EU using population
TYRE WEAR	2020	EU	Rubber	495.99	Scaling from NL to EU using population

8.3.2 *Tyre wear transfers*

As the base input of tyre wear rubber is the starting point of the material flow calculations, the transfer coefficients from the amount going to Urban, Rural and Highways in the Netherlands is estimated using the traffic data from CBS (RWS, 2022), see Table A8. A large part of the highways in the Netherlands are made up of open asphalt (ZOAB) and only a small part is dense asphalt (DAB), for the whole of Europe this is the opposite, although no data was gathered and a rough estimate of 5% ZOAB at EU scale was assumed. In 2020, 80 to 90% of the highways in the Netherlands are made up of ZOAB (Hoeke et al., 2024; RWS, 2022). Between 5 and 10 % of tyre wear is assumed to be PM10 and is emitted to air (Geilenkirchen et al., 2023; Hoeke et al., 2024; Verschoor et al., 2016). The rest of the Tyre wear is either cleaned (Sieber et al., 2020; Verschoor et al., 2016), resuspended by traffic to road-side soil (Verschoor et al., 2016) or further transported by rain runoff. Tyre wear in runoff is either transported to (i) waste water in case of a combined sewer, (ii) stormwater in case of separated sewer, (iii) directly to surface water or (iv) ends up in road side soi, TCs following (Hoeke et al., 2024). Specifically for ZOAB, the cleaned fraction is assumed relatively high (80-90%) due to the entrapment of TWP in the pores and the highway sweeping by the authorities twice a year. Other toad types are assumed to capture between 1 and 2% of Tyre wear due to cleaning (Sieber et al., 2020). A small fraction of the cleaned TWP is assumed to end up in Wastewater (5%) and the rest goes to incineration (Sieber et al., 2020).

Table A8 Transfer coefficients from total tyre wear to road type.

From	***To***	***Year***	***Scale***	***Material***	***Value***	***Source***
Tyre Wear	Highway	2020	NL	Rubber	0.51	CBS data, see RWS, 2022.
Tyre Wear	Urban Roads	2020	NL	Rubber	0.23	CBS data, see RWS, 2022.
Tyre Wear	Rural Roads	2020	NL	Rubber	0.26	CBS data, see RWS, 2022.
Tyre Wear	Highway	2020	EU	Rubber	0.51	Assumption: Same as NL
Tyre Wear	Urban Roads	2020	EU	Rubber	0.23	Assumption: Same as NL
Tyre Wear	Rural Roads	2020	EU	Rubber	0.26	Assumption: Same as NL

8.4 Paint

Microplastics are present in paint as additives and serve diverse purposes such as improving durability, texture, and colour stability. Paint consists of binders, fillers, pigments and solvents. The binders are microplastic polymers. In undried paint, the microplastic content only consists of these binders. When dried, solvents evaporate, and the microplastics bond with the fillers, together forming the microplastic content. As acrylic is the most common plastic polymer used in paint, therefore, the polymer content of paint is modelled as all being acrylic.

In our model, the flow of microplastics from paint is modelled for different types of paint. The MFA for paint starts with an input value for the ‘Paint’ compartment, which equals the total mass of microplastics in paint for a specific year. The microplastic mass fraction depends on the type of paint. The total mass of microplastics in all paint is the sum of the microplastic masses in the different types of paint:

$$M_{MP\ in\ all\ paint} = \sum_{i} Domestic\ paint\ sales \times f_{sector\ i} \times f_{paint\ i} \times f_{MP\ content\ i}$$

where i indicates the type of paint, $Domestic\ paint\ sales$ indicates the mass of paint sold for domestic use, $f_{sector\ i}$ is the fraction of paint sold to the sector to which paint type i belongs, $f_{paint\ i}$ is the fraction of paint type i within the sector, and $f_{MP\ content\ i}$ is the mass fraction of microplastics in paint type i. The values of $f_{sector\ i}$ and $f_{paint\ i}$ were taken from Verschoor et al. (2016). The sector ‘Other paint uses (prof)’ includes road markings. The values of $f_{paint\ i}$ were confidential information from the VVVF (VVVF, 2023), therefore, we assumed equal distributions of the paint types per sector. Figure A2 summarises the paint types and values of the fractions $f_{sector\ i}$, $f_{paint\ i}$, and $f_{MP\ content\ i}$ that were used in the model.

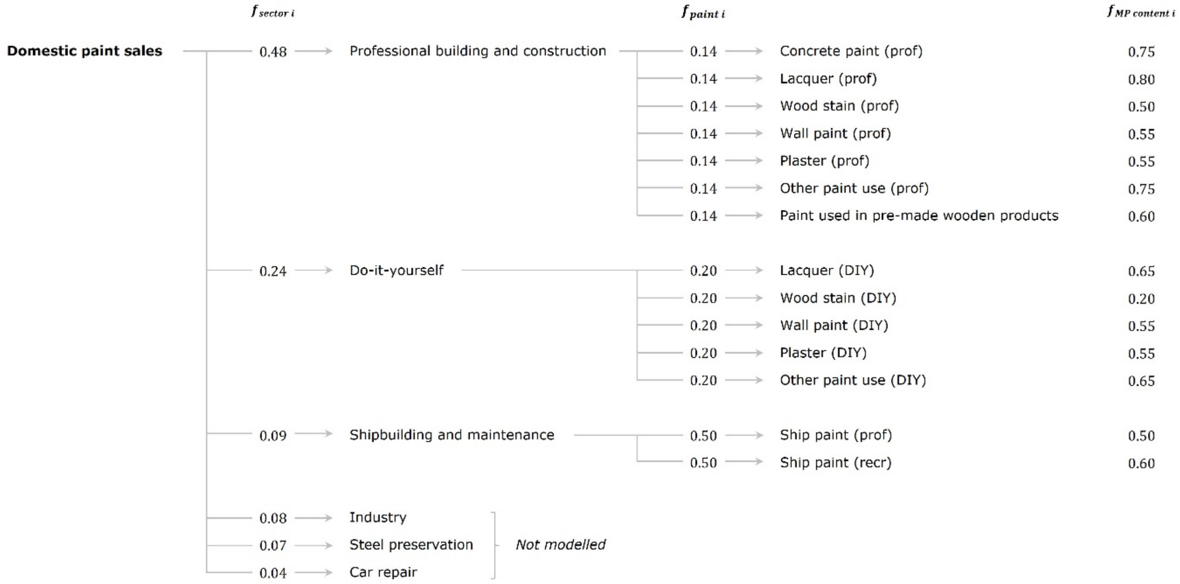


Figure A2 Overview of the paint sectors, paint types and the corresponding values of the fractions.

The domestic paint sales for the Netherlands were obtained from the VVVF for the years 2020, 2021, and 2022: 112.0 kt, 109.5 kt, and 98.2 kt, respectively (VVVF, 2023).Using equation E1.4.1, this yielded a microplastic mass in all paints of 54.1 kt, 52.9 kt, and 47.4 kt, for 2020, 2021, and 2022, respectively. For Europe, the total microplastic mass in all paints used in 2019 was 2326 kt (EC, 2023b).

The transfer coefficients from the microplastic mass in all paints to the microplastic mass in each of the modelled paint types are provided in Table A9. These transfer coefficients were computed on the basis of $f_{sector\ i}$, $f_{paint\ i}$, and $f_{MP\ content\ i}$.

Table A9 Transfer coefficients from microplastic mass content in all paints to the microplastic mass in all paint types i.

From	To (i)	Transfer coefficient
Paint	Concrete paint (prof)	0.107
Paint	Lacquer (prof)	0.114
Paint	Wood stain (prof)	0.071
Paint	Wall paint (prof)	0.078
Paint	Plaster (prof)	0.078
Paint	Other paint uses (prof)	0.107
Paint	Paint used in pre-made wooden products	0.085
Paint	Lacquer (DIY)	0.065
Paint	Wood stain (DIY)	0.020
Paint	Wall paint (DIY)	0.055
Paint	Plaster (DIY)	0.055
Paint	Other paint uses (DIY)	0.065
Paint	Ship paint (prof)	0.047
Paint	Ship paint (recr)	0.056

Physical and chemical processes cause the solid content of paint to weather during its lifetime and release microplastics to the environment. After its lifetime, old paint layers are typically removed through sanding, which can also cause microplastic releases to the environment. Figure A2 depicts the general flow diagram for the modelled paint types of the sectors ‘Professional building and construction’ and ‘Do-it-yourself’ (except for indoor wall paint (DIY). The values of the transfer coefficients in Figure A3 were calculated from fractions reported by Verschoor et al. (2016) and are listed in Table A10.

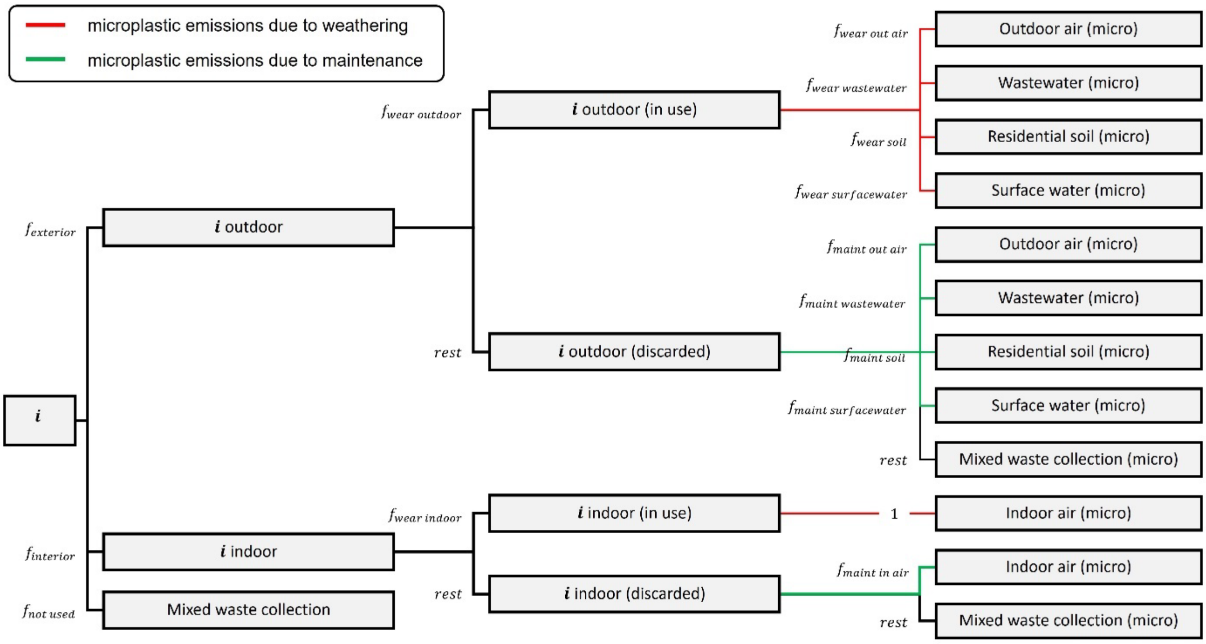


Figure A3 Flow diagram depicting the compartments and flows for all paint types i in the sectors ‘Professional building and construction’ and ‘Do-it-yourself’. With the exception of wall paint (DIY). The transfer coefficients values for all paint types can be found in Table A17.

For indoor use of wall paint (DIY), the emission of microplastics to wastewater as a result of rinsing paint brushes is included in the model. Figure A4 depicts the flow diagram for indoor wall paint (DIY) including an additional factor called f_{brush}, which indicates the mass fraction of microplastics that remains on the paint brush. We followed the assumption by Verschoor et al. (2016) that 100% of the paint on the brush is rinsed off. To compute the value of f_{brush}, we had to account for the lower microplastic mass content in liquid paint, which only consists of microplastic binders, compared to dried up paint. As our model input is expressed in mass of microplastics in paint, and not mass of paint, we need to know the fraction of only microplastic binders in the solid microplastic content. This can be computed by multiplying the solid paint content (binders + fillers) in wall paint (DIY), i.e. 55% ($f_{MP\ content\ i} = 0.55$; see Figure A1), with the binder content in wall paint (DIY), i.e. 5% (Verschoor et al., 2016). This yields: (100*5)/55 = 9.1% of the solid paint content in wall paint (DIY) consists of microplastic binders. Subsequently, we multiply this with the fraction of paint left of the brush, which is 1.6% (Verschoor et al., 2016): f_{brush} = 0.091*0.016 = 0.001456.

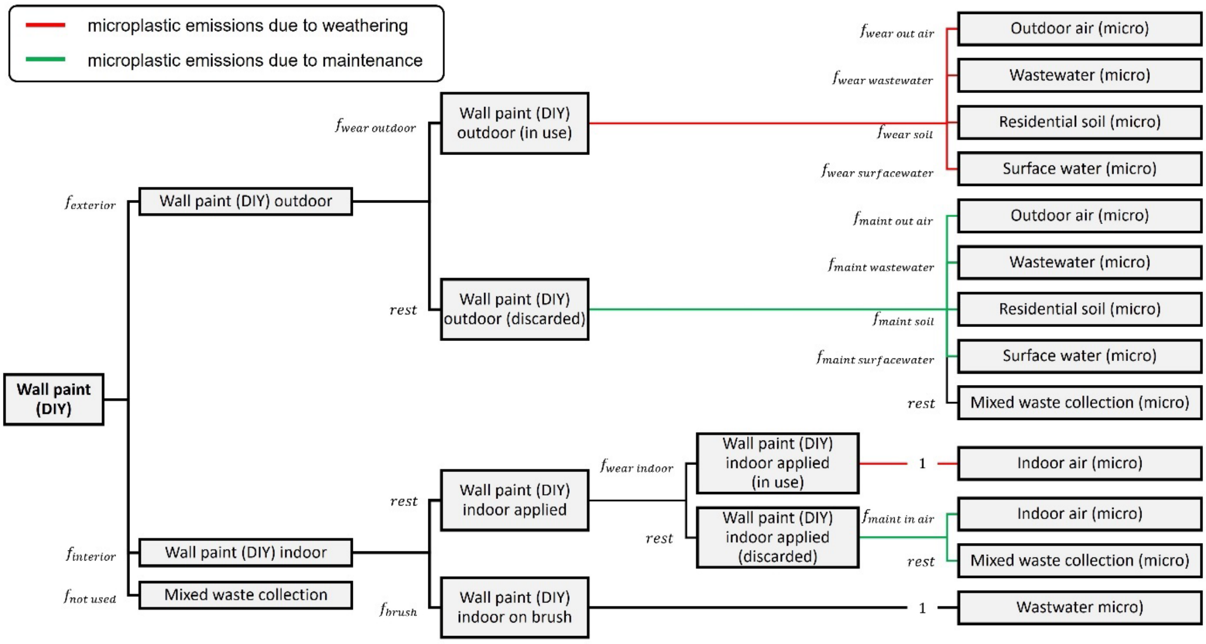


Figure A4 Flow diagram depicting the compartments and flows for 'Wall paint (DIY)'. f_{brush} = 0.001456, the remaining transfer coefficient values can be found in Table A17.

Figure A5 depicts the flow diagram for the microplastic flows from paint used in the sector 'Ship building and maintenance'. Microplastics are emitted from paint on ships to surface water due to wear and during the removal of old paint layers. The values for the transfer coefficients indicated in Figure A5 are provided in Table A11.

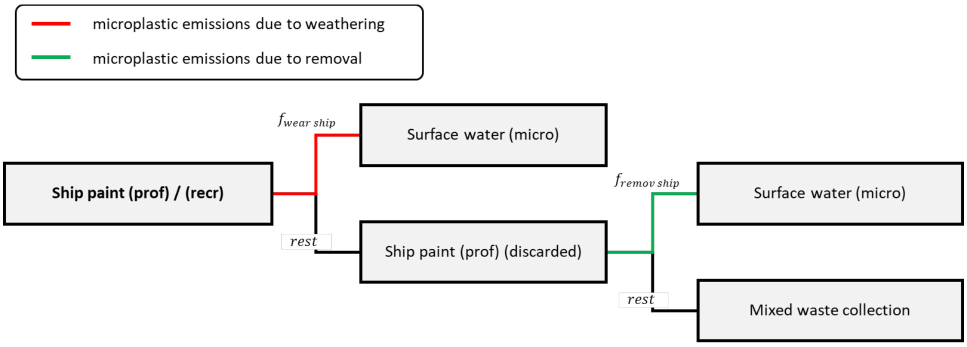


Figure A5 Flow diagram depicting the compartments and flows for the two paint types in the 'ship building and maintenance' sector. The transfer coefficient values can be found in Table A18

Table A10 Transfer coefficients for all paint types i in the sectors ‘Professional building and construction’ and ‘Do-it-yourself’.

Paint type (i)	$f_{exterior}$ 1	$f_{interior}$ 2	$f_{not\ used}$ 3	$f_{wear\ outdoor}$ 4	$f_{wear\ indoor}$ 5	$f_{wear\ out\ air}$ 6	$f_{wear\ wastewat}$ 7	$f_{wear\ soil}$ 8	$f_{wear\ surfacew}$ 9	$f_{maint\ out\ air}$ 10	$f_{maint\ wastewa}$ 11	$f_{maint\ soil}$ 12	$f_{maint\ surfacew}$ 13	$f_{maint\ in\ air}$ 14
Concrete paint (prof)	0.4850	0.4850	0.0300	0.0300	0.0030	0.05	0.394	0.522	0.034	0.00160	0.01260	0.0167	0.0011	0.032
Lacquer (prof)	0.3880	0.5820	0.0300	0.0300	0.0030	0.05	0.394	0.522	0.034	0.00160	0.01260	0.0167	0.0011	0.032
Wood stain (prof)	0.2425	0.7275	0.0300	0.0300	0.0030	0.05	0.394	0.522	0.034	0.00160	0.01260	0.0167	0.0011	0.032
Wall paint (prof)	0.0679	0.9021	0.0300	0.0300	0.0030	0.05	0.394	0.522	0.034	0	0	0	0	0
Plaster (prof)	0.0291	0.9409	0.0300	0.0300	0.0030	0.05	0.394	0.522	0.034	0	0	0	0	0
Other paint uses (prof)	0.0970	0.8730	0.0300	0.0300	0.0030	0.05	0.394	0.522	0.034	0	0	0	0	0
Paints used in pre-made wooden products	0.2425	0.7275	0.0300	0.0300	0.0030	0.05	0.394	0.522	0.034	0.00160	0.01260	0.0167	0.0011	0.032
Lacquer (DIY)	0.3400	0.5100	0.1500	0.0300	0.0030	0.05	0.394	0.522	0.034	0.0032	0.02522	0.03341	0.00218	0.064
Wood stain (DIY)	0.5100	0.3400	0.1500	0.15	0.015	0.05	0.394	0.522	0.034	0	0	0	0	0
Wall paint (DIY)	0.0000	0.8500	0.1500	0.0300	0.0030	0.05	0.394	0.522	0.034	0	0	0	0	0
Plaster (DIY)	0.0000	0.8500	0.1500	0.0300	0.0030	0.05	0.394	0.522	0.034	0	0	0	0	0
Other paint uses (DIY)	0.0000	0.8500	0.1500	0.0300	0.0030	0.05	0.394	0.522	0.034	0.0032	0.02522	0.03341	0.00218	0.064

[1] Calculated from the f_{used} and $f_{exterior}$ factors provided by Verschoor et al. (2016): $f_{used} * f_{exterior}$

[2] Calculated from the $f_{exterior}$ and f_{used} factors: $f_{used} * (1 - f_{exterior})$

[3] Calculated from the f_{used} factor from Verschoor et al. (2016): 1 - f_{used}

[4] Equal to the EF_{wear} factor from Verschoor et al. (2016)

[5] Assume that the wear of indoor paint is 10 times lower than the wear of outdoor paint: $0.1 * EF_{wear}$

[6] Assume that 5% of the microplastics emitted during the wear of paint go to outdoor air. This fraction is the same as the fraction of tyre wear particles that go to outdoor air.

[7] Equal to the "overall value" of microplastic emissions to sewerage reported in Table 10 from Verschoor et al. (2016): 39.4%

[8] Derived from the "overall value" of microplastic emissions to soil reported in Table 10 from Verschoor et al. (2016) = 57%. However, the emission factors in Table 10 do not sum up to 100%. Therefore, we adjust the 57% to 57.2%. Then we subtracted 5% of the 57.2% because we assumed 5% goes to air. Thus (57.2 - 5 =) 52.2% goes to soil.

[9] Equal to the "overall value" of microplastic emissions to surface water reported in Table 10 from Verschoor et al. (2016) = 3.4%

[10] Calculated from the $EF_{removal}$ factor from Verschoor et al. (2016) and $f_{wear\ out\ air}$: $EF_{removal} * f_{wear\ out\ air}$

[11] Calculated from the $EF_{removal}$ factor from Verschoor et al. (2016) and $f_{wear\ wastewater}$: $EF_{removal} * f_{wear\ wastewater}$

[12] Calculated from the $EF_{removal}$ factor from Verschoor et al. (2016) and $f_{wear\ soil}$: $EF_{removal} * f_{wear\ soil}$

[13] Calculated from the $EF_{removal}$ factor from Verschoor et al. (2016) and $f_{wear\ surfacewater}$: $EF_{removal} * f_{wear\ surfacewater}$

[14] Equal to the $EF_{removal}$ factor from Verschoor et al. (2016)

Table A11 Transfer coefficients for the two paint types i in the sector 'Ship building and maintenance'.

Paint type (i)	$f_{wear\ ship}$[1]	$f_{remov\ ship}$[2]
Ship paint (prof)	0.0100	0.0100
Ship paint (recr)	0.0100	0.0500

[1] Equal to the EF_{wear} factor in Table 13 from Verschoor et al. (2016)
[2] Equal to the $Overall\ EF$ value in Table 12 from Verschoor et al. (2016)

8.5 Textiles

Plastic polymers are used in the production of fabrics and textile products. Plastic fibres are mixed with natural fibres to enhance the performance and functionality of textiles for various applications. By employing techniques like coating, blending, or extrusion, plastic polymers are seamlessly integrated into fabrics, giving rise to properties such as waterproofing, durability, flexibility, elasticity, and resistance to wrinkles or flames. In the model, the flow of microplastics fibres from textiles is modelled for different textile categories. The textile categorisation that we use (established by TNO) is shown in Table A12.

Table A12 Textile categorisation.

Main category	**Sub-category**	**Description/examples**
Clothing (product sector)	Clothing (in use)	Jackets, trousers, sweaters, t-shirts
Household textiles (product sector)	Disposable cleaning cloths	-
	Wet wipes	-
	Tampons	-
	Panty liners	-
	Sanitary pads	-
	Home textiles (in use)	Bedsheets, bath towels
Technical textiles	Technical home textiles (in use)	Carpets
	Medical textiles	Face masks
	Agrotextiles (in use)	
	Mobility textiles	Car seats
	Geotextiles (in use)	
	Building textiles (in use)	
	Other technical textiles	
	Textile coating (in use)	Waterproof rain jacket

8.5.1 *Netherlands scale*

The microplastic fibre masses of the sub-categories at NL scale are listed in Table A13. For the categories ‘Clothing (in use)’, ’Home textiles (in use)’, and ‘Technical home textiles (in use)’ the microplastic masses were calculated based on data from the Centraal Bureau voor de Statistiek (CBS) and the following equation:

$$M_i = total\ textile\ consumption \times f_i \times f_{fibre} \qquad \text{(E1.6.1)}$$

with i the textile category, f_i the mass fraction of textile category i, and f_{fibre} the mass fraction of microplastic fibres. The $total\ textile\ consumption$ in 2019 in the Netherlands was 646 kt (CBS, 2021).In 2019 the textile stock in the Netherlands consisted for 7.3% of clothing, 7.1% of home textiles, and 26.6% of technical home textiles (CBS, 2021).
The synthetic fibre content for all textiles was set to 63% based on reported percentages between 60% and 67% (Boucher and Friot, 2017; EEA, 2019).
Assuming a synthetic fibre content of 63% for all textiles, the microplastic fibre masses for ‘Clothing (in use)’, ‘Home textiles (in use)’, and ‘Technical home textiles (in use)’ were calculated using E1.6.1: 29.57 kt, 28.97 kt, and 108.41 kt, respectively. For the sub-category ‘Geotextiles (in use)’ we adopted the estimate reported by Voskamp and Retzlaff (2022). For the remaining sub-categories we adopted the estimates reported by (D. Kawecki and Nowack, 2019). Finally, the mass of microplastic fibres for the sub-category ‘Other technical textiles’ was calculated by subtracting the sum of masses from the other sub-categories from the total microplastic fibre mass, which was 407 kt (63% of 646 kt). This yielded a microplastic fibre mass of 38.98 kt for the sub-category ‘Other technical textiles’ (Table A13). The last column in Table A13 contains the mass fractions of each of the sub-categories with respect to the total mass of microplastic fibres.

Table A13 Microplastic fibre masses for the modelled textile sub-categories for the Netherlands for 2019.

Sub-category	Microplastic mass (kt)	Reference	Fraction of total mass
Clothing (in use)	29.57	CBS (2019)	7.3%
Disposable cleaning cloths	1.63	Kawecki and Nowack (2019)	0.4%
Wet wipes	5.70	Kawecki and Nowack (2019)	1.4%
Tampons	1.22	Kawecki and Nowack (2019)	0.3%
Panty liners	0.41	Kawecki and Nowack (2019)	0.1%
Sanitary pads	10.58	Kawecki and Nowack (2019)	2.6%
Home textiles (in use)	28.97	CBS (2019)	7.1%
Technical home textiles (in use)	108.41	CBS (2019)	26.6%
Medical textiles	56.98	Kawecki and Nowack (2019)	14.0%

Sub-category	**Microplastic mass (kt)**	**Reference**	**Fraction of total mass**
Agrotextiles (in use)	40.29	Kawecki and Nowack (2019)	9.9%
Mobility textiles	47.62	Kawecki and Nowack (2019)	11.7%
Geotextiles (in use)	11.40	Voskamp and Retzlaff (2022)	2.8%
Building textiles (in use)	15.06	Kawecki and Nowack (2019)	3.7%
Other technical textiles	38.98	*calculated*	9.6%
Textile coating (in use)	10.18	Kawecki and Nowack (2019)	2.5%
Sum:	**407.00**		**100%**

8.5.2 *European Union scale*

The textile consumption in the European Union in 2017 was 25.9 kg per person per year (European Economic Area (EEA)). Based on a European population of 511.8 million (Eurostat, 2017).a total textile consumption of 13255.62 kt was estimated for the European Union in 2017. Using a synthetic fibre content of 63%, this yielded a microplastic fibre mass of 8351.04 kt. The microplastic fibre masses of the sub-categories at EU scale are listed in Table A14. The masses of microplastic fibres for the sub-categories, except for ‘Geotextiles (in use)’ and ‘Other technical textiles’, were calculated using the mass fractions listed in the last column of Table A13. Geotextile use in the European Union in 2022 was estimated at 200 kt by Voskamp and Retzlaff (2022). The microplastic fibre mass of ‘Other technical textiles’ was calculated by subtracting the sum of masses from the other sub-categories from the total microplastic fibre mass. This yielded a microplastic fibre mass of 833.72 kt for the sub-category ‘Other technical textiles’ (Table A14).

Table A14 Microplastic fibre masses for the modelled textile sub-categories for the European Union for 2017.

Sub-category	**Microplastic mass (kt)**
Clothing (in use)	606.73
Disposable cleaning cloths	33.45
Wet wipes	116.96
Tampons	25.03
Panty liners	8.41
Sanitary pads	217.09
Home textiles (in use)	594.42
Technical home textiles (in use)	2224.41
Medical textiles	1169.15
Agrotextiles (in use)	826.69
Mobility textiles	977.09
Geotextiles (in use)	200.00
Building textiles (in use)	309.01
Other technical textiles	833.72
Textile coating (in use)	208.88
Sum:	**8351.04**

8.5.3 *Plastic polymer content*

Plastic polymers that are used in textiles are HDPE, PP, PVC, PET, PA (polyamide), and acrylic. The mass fractions of the different plastic polymers in each textile sub-category are summarised in Table A15. When the mass fractions was not available, we assumed equal proportionalities. Using the mass fractions of the plastic polymers, the total mass for each polymer was calculated for all sub-categories. The sum of these masses yielded the total polymer masses for the (Table A16).

Table A15 Mass fractions of the plastic polymers in the textile sub-categories.

Sub-category	**HDPE (%)**	**PP (%)**	**PVC (%)**	**PET (%)**	**PA (%)**	**Acrylic (%)**	**Reference**
Clothing (in use)	1.0	1.0	0.0	77.0	12.0	9.0	(1)
Disposable cleaning cloths	0.0	0.0	0.0	50.0	50.0	0.0	(2)
Wet wipes	50.0	0.0	0.0	50.0	0.0	0.0	(2)
Tampons	50.0	0.0	0.0	50.0	0.0	0.0	(2)
Panty liners	0.0	100.0	0.0	00.0	0.0	0.0	(2)
Sanitary pads	33.3	33.3	0.0	33.3	0.0	0.0	(2)
Home textiles (in use)	1.0	1.0	0.0	77.0	12.0	9.0	(1)
Technical home textiles (in use)	0.0	20.0	0.0	25.0	50.0	5.0	(3)
Medical textiles	0.0	25.0	0.0	25.0	25.0	25.0	(4)
Agrotextiles (in use)	0.0	33.3	0.0	33.3	33.3	0.0	(2)
Mobility textiles	0.0	33.3	0.0	33.3	33.3	0.0	(2)
Geotextiles (in use)	2.0	92.0	0.0	5.0	1.0	0.0	(5)
Building textiles (in use)	0.0	33.3	0.0	33.3	33.3	0.0	(2)
Other technical textiles	0.0	33.3	0.0	33.3	33.3	0.0	(2)
Textile coating (in use)	0.0	0.0	100	0.0	0.0	0.0	(2)

(1) ‘Synthetic fibers’ from polymerdatabase (2023)
(2) Kawecki and Nowack (2019)
(3) ‘Carpet fibres’ from polymerdatabase (2023)
(4) Thadepalli (2022)
(5) Wu et al. (2020)

Table A16 Microplastic polymer masses for three main textile categories.

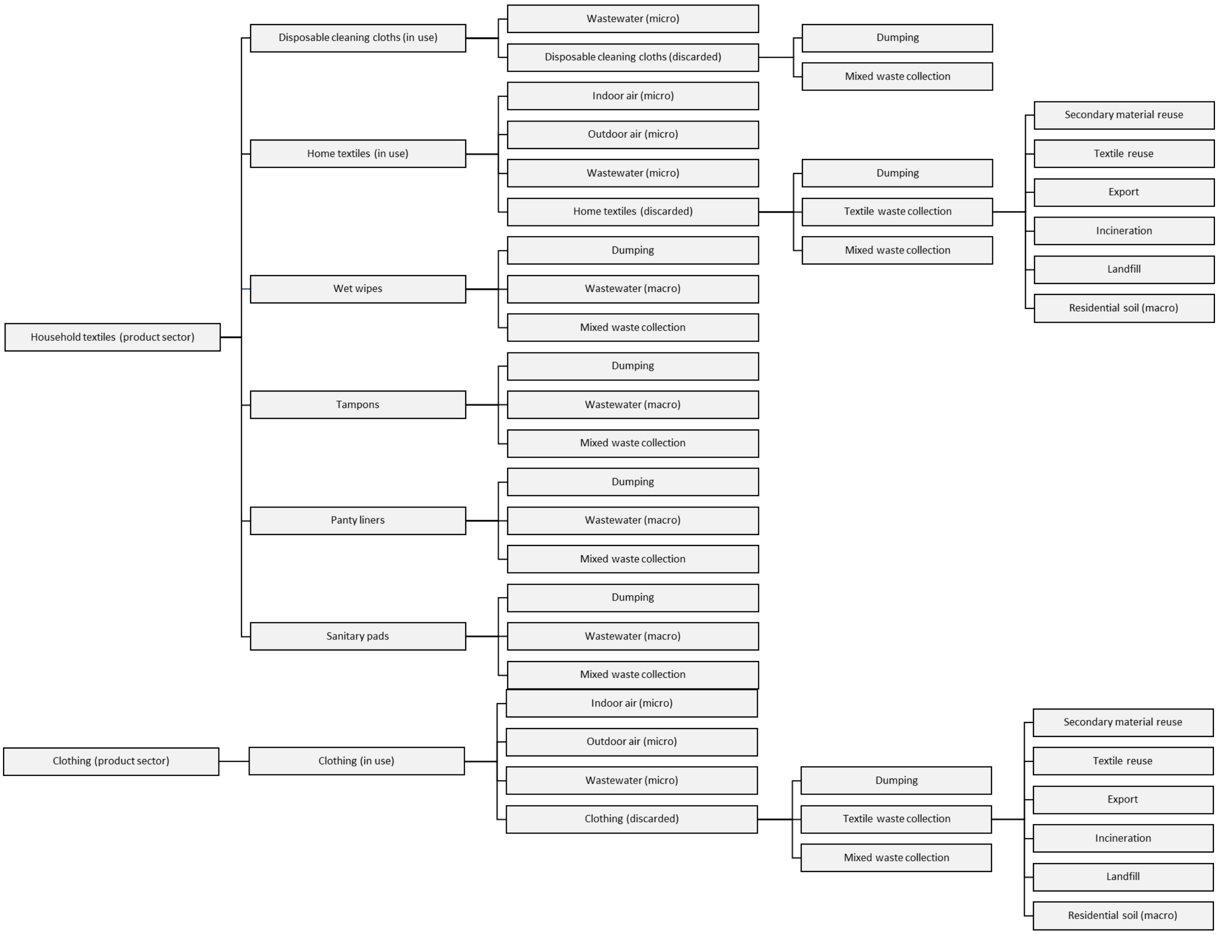
Main category	**HDPE (kt)**	**PP (kt)**	**PVC (kt)**	**PET (kt)**	**PA (kt)**	**Acrylic (kt)**	**Scale**
Clothing (product sector)	0.30	0.30	0.00	22.77	3.55	2.66	NL
Household textiles (product sector)	7.28	4.23	0.00	30.11	4.29	2.61	NL
Technical textiles	0.23	93.73	10.18	89.23	115.88	19.67	NL
Clothing (product sector)	6.07	6.07	0.00	467.18	72.81	54.61	EU

Main category	HDPE (kt)	PP (kt)	PVC (kt)	PET (kt)	PA (kt)	Acrylic (kt)	Scale
Household textiles (product sector)	149.30	86.72	0.00	617.78	88.05	53.50	EU
Technical textiles	4.00	1903.34	208.88	1840.56	2388.67	403.51	EU

These polymer masses are the input values that were used in the model for the Netherlands (for 2019) and for the European Union (for 2017).

8.5.4 *Transfer coefficients*

During the lifetime of textiles, microplastic fibres can be emitted to air due to wear or to wastewater due to washing. Limited data was available on microplastic loss due to drying, hence this is not included. After its lifetime, textiles are discarded and end up in dumpsites, mixed waste collection, textile reuse, or incinerable waste collection. All modelled microplastic fibre flows from textiles are shown in the flow diagram in Figure A6. The transfer coefficients for all flows in Figure A6 are listed in Table A17. The transfer coefficient for microplastic emissions from washing is an average value based on seven studies (see Table A18).



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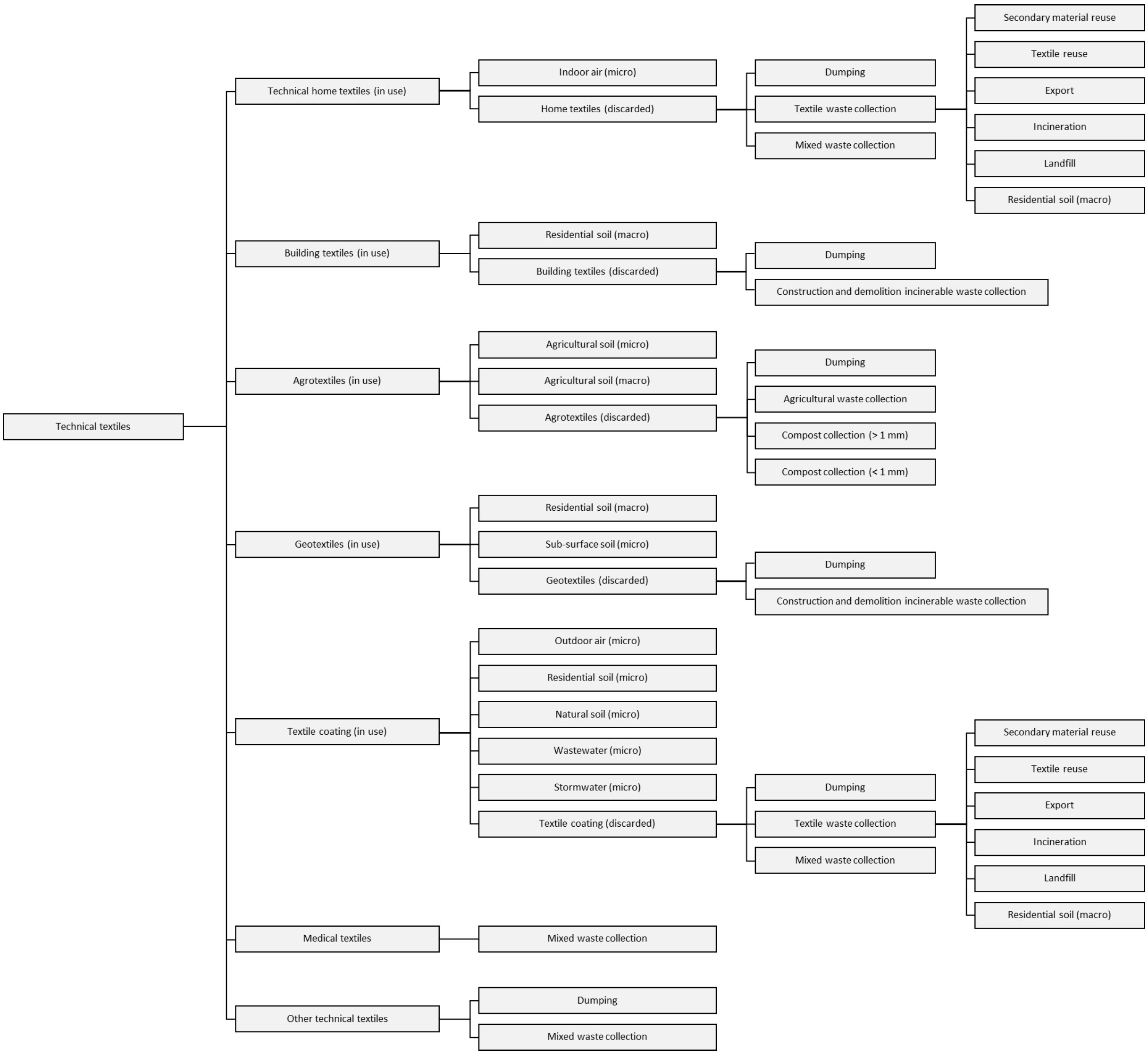

Figure A6 Flow diagram depicting the compartments and flows for textiles.

Table A17 Transfer coefficients for all textile flows depicted in Figure A6.

From	To	Transfer coefficient	Source	Comments
Clothing (in use)	Indoor air (micro)	0.00037	Kawecki and Nowack (2019)	0.04% wear and tear, of which 93% goes to indoor air
Clothing (in use)	Indoor air (micro)	0.00800	Kawecki and Nowack (2019)	0.86% wear and tear, of which 93% goes to indoor air
Clothing (in use)	Outdoor air (micro)	0.00003	Kawecki and Nowack (2019)	0.04% wear and tear, of which 7% goes to outdoor air
Clothing (in use)	Outdoor air (micro)	0.00060	Kawecki and Nowack (2019)	0.86% wear and tear, of which 7% goes to outdoor air
Clothing (in use)	Wastewater (micro)	0.01757	*Average from several sources*	See Table 1.6.7
Clothing (in use)	Clothing (discarded)	rest		
Clothing (discarded)	Dumping	0.00027	Kawecki and Nowack (2019)	
Clothing (discarded)	Mixed waste collection	0.55385	Massabalans textiel (2018)	
Clothing (discarded)	Textile waste collection	0.44588	Massabalans textiel (2018)	
Disposable cleaning cloths	Wastewater (micro)	0.01757	*Average from several sources*	See Table 1.6.7
Disposable cleaning cloths	Dumping	0.00027	Kawecki and Nowack (2019)	
Disposable cleaning cloths	Mixed waste collection	rest		
Wet wipes	Dumping	0.00027	Kawecki and Nowack (2019)	
Wet wipes	Mixed waste collection	rest		

From	To	Transfer coefficient	Source	Comments
Wet wipes	Wastewater (macro)	0.06500	Kawecki and Nowack (2019)	Flushing probability
Wet wipes	Wastewater (macro)	0.46000	Kawecki and Nowack (2019)	Flushing probability
Tampons	Dumping	0.00027	Kawecki and Nowack (2019)	
Tampons	Mixed waste collection	rest		
Tampons	Wastewater (macro)	0.91400	Kawecki and Nowack (2019)	Flushing probability
Panty liners	Dumping	0.00027	Kawecki and Nowack (2019)	
Panty liners	Mixed waste collection	rest		
Panty liners	Wastewater (macro)	0.16500	Kawecki and Nowack (2019)	Flushing probability
Panty liners	Wastewater (macro)	0.52500	Kawecki and Nowack (2019)	Flushing probability
Sanitary pads	Dumping	0.00027	Kawecki and Nowack (2019)	
Sanitary pads	Mixed waste collection	rest		
Sanitary pads	Wastewater (macro)	0.06500	Kawecki and Nowack (2019)	Flushing probability
Home textiles (in use)	Indoor air (micro)	0.01300	Kawecki and Nowack (2019)	1.3% shedding rate, of which 100% goes to indoor air
Home textiles (in use)	Indoor air (micro)	0.00860	Kawecki and Nowack (2019)	0.86% shedding rate, of which 100% goes to indoor air
Home textiles (in use)	Outdoor air (micro)	0.00000	Kawecki and Nowack (2019)	

From	To	Transfer coefficient	Source	Comments
Home textiles (in use)	Wastewater (micro)	0.01757	*Average from several sources*	See Table 1.6.7
Home textiles (in use)	Home textiles (discarded)	rest		
Home textiles (discarded)	Dumping	0.00027	Kawecki and Nowack (2019)	
Home textiles (discarded)	Mixed waste collection	0.55385	Massabalans textiel (2018)	
Home textiles (discarded)	Textile waste collection	0.44588	Massabalans textiel (2018)	
Technical home textiles (in use)	Indoor air (micro)	0.01300	Kawecki and Nowack (2019)	1.3% shedding rate, of which 100% goes to indoor air
Technical home textiles (in use)	Indoor air (micro)	0.00860	Kawecki and Nowack (2019)	0.86% shedding rate, of which 100% goes to indoor air
Technical home textiles (in use)	Technical home textiles (discarded)	rest		
Technical home textiles (discarded)	Dumping	0.00027	Kawecki and Nowack (2019)	

From	To	Transfer coefficient	Source	Comments
Technical home textiles (discarded)	Mixed waste collection	0.55385	Massabalans textiel (2018)	
Technical home textiles (discarded)	Textile waste collection	0.44588	Massabalans textiel (2018)	
Medical textiles	Mixed waste collection	1.00000	Kawecki and Nowack (2019)	
Agrotextiles (in use)	Agricultural soil (micro)	0.00000	Kawecki and Nowack (2019)	Best case scenario
Agrotextiles (in use)	Agricultural soil (micro)	0.01300	Kawecki and Nowack (2019)	
Agrotextiles (in use)	Agricultural soil (macro)	0.00000	Kawecki and Nowack (2019)	Best case scenario
Agrotextiles (in use)	Agricultural soil (macro)	0.08500	Kawecki and Nowack (2019)	
Agrotextiles (in use)	Agrotextiles (discarded)	rest		
Agrotextiles (discarded)	Agricultural waste collection	rest		
Agrotextiles (discarded)	Dumping	0.00027	Kawecki and Nowack (2019)	
Agrotextiles (discarded)	Collected organic waste	0.038	Kawecki and Nowack (2019)	
Mobility textiles	Export	0.53527	Kawecki and Nowack (2019)	
Mobility textiles	ELV textiles collection	rest		
Geotextiles (in use)	Residential soil (macro)	0.00130	Kawecki and Nowack (2019)	

From	To	Transfer coefficient	Source	Comments
Geotextiles (in use)	Residential soil (macro)	0.01470	Kawecki and Nowack (2019)	
Geotextiles (in use)	Sub-surface soil (micro)	0.00000	Kawecki and Nowack (2019)	
Geotextiles (in use)	Sub-surface soil (micro)	0.01200	Kawecki and Nowack (2019)	1.2% wear and tear, of which 100% goes to subsurface soil
Geotextiles (in use)	Geotextiles (discarded)	rest		
Geotextiles (discarded)	Construction and demolition incinerable waste collection	rest		
Geotextiles (discarded)	Dumping	0.00027	Kawecki and Nowack (2019)	
Building textiles (in use)	Residential soil (macro)	0.00130	Kawecki and Nowack (2019)	
Building textiles (in use)	Residential soil (macro)	0.01470	Kawecki and Nowack (2019)	
Building textiles (in use)	Building textiles (discarded)	rest		
Building textiles (discarded)	Construction and demolition incinerable waste collection	rest		
Building textiles (discarded)	Dumping	0.00027	Kawecki and Nowack (2019)	
Other technical textiles	Dumping	0.00027	Kawecki and Nowack (2019)	

From	To	Transfer coefficient	Source	Comments
Other technical textiles	Mixed waste collection	rest		
Textile coating (in use)	Outdoor air (micro)	0.00040	Kawecki and Nowack (2019)	0.04% wear and tear, of which 100% goes to outdoor air
Textile coating (in use)	Outdoor air (micro)	0.00860	Kawecki and Nowack (2019)	0.86% wear and tear, of which 100% goes to outdoor air
Textile coating (in use)	Residential soil (micro)	0.00250	Kawecki and Nowack (2019)	Assumption
Textile coating (in use)	Natural soil (micro)	0.00250	Kawecki and Nowack (2019)	Assumption
Textile coating (in use)	Wastewater (micro)	0.00250	Kawecki and Nowack (2019)	Assumption
Textile coating (in use)	Stormwater (micro)	0.00250	Kawecki and Nowack (2019)	Assumption
Textile coating (in use)	Textile coating (discarded)	rest		
Textile coating (discarded)	Dumping	0.00027	Kawecki and Nowack (2019)	
Textile coating (discarded)	Mixed waste collection	rest	Kawecki and Nowack (2019)	

From	To	Transfer coefficient	Source	Comments
Textile coating (discarded)	Textile waste collection	0.33810	Kawecki and Nowack (2019)	
Textile waste collection	Secondary material reuse	0.01440	FFact (2020)	
Textile waste collection	Export	0.84000	FFact (2020)	
Textile waste collection	Textile reuse	0.04480	FFact (2020)	
Textile waste collection	Landfill	0.00300	FFact (2020)	
Textile waste collection	Incineration	0.09600	FFact (2020)	
Textile waste collection	Residential soil (macro)	rest		

The transfer coefficients are independent of the region, i.e. they apply at the scale of the Netherlands and the European Union. For some flows more than one transfer coefficient value is provided. The model fits a distribution through all transfer coefficient values and picks one value for each model run.

Table A18 Literature search of microplastic losses from washing (use phase).

From	To	Transfer coefficient	Polymer	Source
Clothing (in use)	Waste water (MP)	0.000700	Acrylic-PA	Belzagui et al. (2019)
Clothing (in use)	Waste water (MP)	0.000200	Polyester	Belzagui et al. (2019)

From	To	Transfer coefficient	Polymer	Source
Clothing (in use)	Waste water (MP)	0.000003	Polyester	Napper and Thompson (2016)
Clothing (in use)	Waste water (MP)	0.000001	Polyester-cotton	Napper and Thompson (2016)
Clothing (in use)	Waste water (MP)	0.000002	Acrylic	Napper and Thompson (2016)
Clothing (in use)	Waste water (MP)	0.000060	Polyester	Hernandez et al. (2017)
Clothing (in use)	Waste water (MP)	0.000001	Polyester (weave)	De Falco et al. (2018)
Clothing (in use)	Waste water (MP)	0.000002	Polyester (knit)	De Falco et al. (2018)
Clothing (in use)	Waste water (MP)	0.000001	PP	De Falco et al. (2018)
Clothing (in use)	Waste water (MP)	0.000400	Polyester	Sillanpää and Sainio (2017)
Clothing (in use)	Waste water (MP)	0.004000	Polyester	Hartline et al. (2016)
Clothing (in use)	Waste water (MP)	0.000012	Polyester	Pirc et al. (2016)
Average:		**0.01757**		

8.6 Agriculture

Plastic products are widely used in agriculture for multiple applications. Products include agricultural mulch films, irrigation pipes, seed coatings and greenhouse coverings. In this research, the agricultural plastics are divided into four categories: mulching films, greenhouse films, pipes and other plastic products, as the films and pipes make up most of the plastic consumption in agriculture (Hofmann et al., 2023; Urbanus et al., 2022).

8.6.1 European Union input data

Input data on agricultural plastic consumption in Europe was obtained from the Agricultural Plastics Environment for the years 2018 and 2019 ("Statistics - APE Europe," n.d.). In 2019, 695.5 kt of plastic was used in the EU. This total plastic mass was divided into different compartments and materials by using fractions defined by the FAO (FAO, 2021). Firstly, the total mass of plastic for each year was divided in one of four compartments: mulching films, pipes, other, and greenhouse films (Table A19). Each of these compartments is divided between different polymers (FAO, 2021) (Table A20). Finally, the mass for each polymer in a compartment was summed with the masses of the same polymer in the other compartments. This gives a division of the total agricultural plastics per year per polymer.

Table A19 European agricultural plastic consumption divided between 4 different compartments, based on FAO (2021).

Compartment	% of total agricultural plastic consumption
Agricultural mulching films	63
Agricultural pipes	6
Agricultural other	13
Agricultural greenhouse films	16

Table A20 Agricultural plastic consumption divided between polymers, per compartment.

	Agricultural mulching films	Agricultural pipes	Agricultural other	Agricultural greenhouse films
	%	%	%	%
PVC	5.0	24.0	20.0	5.0
LDPE	95.0	72.0	67.0	95.0
HDPE	0.0	4.0	4.3*	0.0
PP	0.0	0.0	4.3*	0.0
PS	0.0	0.0	4.3*	0.0

Assumed to be the same for NL and EU (Urbanus et al., 2022).
* No data was available on the distribution of HDPE, PP and PS in the Agriculture Other compartment. It is assumed that the fractions of these polymers are evenly distributed.

8.6.2 Netherlands input data

Input data for the Netherlands was calculated as the input data for Europe multiplied by two different fractions (Table A23). This gave a high and a low estimate of agricultural plastic consumption for the years

2018 and 2019. For 2019, this resulted in a total agricultural plastic consumption of between 22.9 and 46.7 kt.
The division between the different compartments was made using percentages provided by Urbanus et al. (2022) combined with fractions from FAO (2021) (Table A24). The division between polymers within the compartments is the same as for EU (Table A22).

Table A21 Fractions used to calculate NL agricultural plastic consumption.

Fraction type	Year	Value	Source
Fraction NL (plant + lifestock + Gardening) from EU (plant + lifestock + Gardening) total consumption	2022	3.36%	Plastics Europe (2024)
Market share agricultural industry	2022	6.71%	Eurostat (2024)

Table A22 Netherlands agricultural plastic consumption divided between 4 different compartments, based on FAO (2021).

Compartment	% of total agricultural plastic consumption
Agricultural mulching films	53
Agricultural pipes	18
Agricultural other	11
Agricultural greenhouse films	14

8.6.3 *Lifetimes*

The compartments Agricultural pipes and Agricultural greenhouse films have lifetimes. The lifetimes of these compartments are 80 years and 4 years respectively (D. Kawecki and Nowack, 2019). See Excel input file for the distribution of emissions of these lifetimes.

8.6.4 *Transfer coefficients*

Transfer coefficients from Agriculture to each of the subsequent compartments were calculated using the data mentioned in the ‘European union input data’ and ‘Netherlands input data’ sections. For transfer coefficients to compost see Appendix 7.1.8.1. Other transfer coefficients pertaining to agriculture were taken from Kawecki and Nowack (2019) (Table A23).

Table A23 All transfer coefficients for agriculture.

From	To	Scale	Material	Value	Source
Agriculture	Agricultural pipes (discarded)	NL	PVC	0.4071	Urbanus et al. (2022)
Agriculture	Agricultural pipes (discarded)	NL	LDPE	0.1431	Urbanus et al. (2022)
Agriculture	Agricultural pipes (discarded)	NL	HDPE	0.5617	Urbanus et al. (2022)
Agriculture	Agricultural pipes (in use)	NL	PVC	0.0327	Urbanus et al. (2022)
Agriculture	Agricultural pipes (in use)	NL	LDPE	0.0115	Urbanus et al. (2022)

From	To	Scale	Material	Value	Source
Agriculture	Agricultural pipes (in use)	NL	HDPE	0.0451	Urbanus et al. (2022)
Agriculture	Agricultural other	NL	PVC	0.2192	Urbanus et al. (2022)
Agriculture	Agricultural other	NL	PS	1.0000	Urbanus et al. (2022)
Agriculture	Agricultural other	NL	PP	1.0000	Urbanus et al. (2022)
Agriculture	Agricultural other	NL	LDPE	0.0861	Urbanus et al. (2022)
Agriculture	Agricultural other	NL	HDPE	0.3932	Urbanus et al. (2022)
Agriculture	Agricultural greenhouse films (discarded)	NL	PVC	0.0627	Urbanus et al. (2022)
Agriculture	Agricultural greenhouse films (discarded)	NL	LDPE	0.1396	Urbanus et al. (2022)
Agriculture	Agricultural greenhouse films (in use)	NL	PVC	0.0064	Urbanus et al. (2022)
Agriculture	Agricultural greenhouse films (in use)	NL	LDPE	0.0142	Urbanus et al. (2022)
Agriculture	Agricultural pipes (discarded)	EU	PVC	0.1673	Assessment of agricultural plastics and their sustainability, 2021
Agriculture	Agricultural pipes (discarded)	EU	LDPE	0.0454	Assessment of agricultural plastics and their sustainability, 2021
Agriculture	Agricultural pipes (discarded)	EU	HDPE	0.2784	Assessment of agricultural plastics and their sustainability, 2021
Agriculture	Agricultural pipes (in use)	EU	PVC	0.0134	Assessment of agricultural plastics and their sustainability, 2021
Agriculture	Agricultural pipes (in use)	EU	LDPE	0.0036	Assessment of agricultural plastics and

From	To	Scale	Material	Value	Source
					their sustainability, 2021
Agriculture	Agricultural pipes (in use)	EU	HDPE	0.0223	Assessment of agricultural plastics and their sustainability, 2021
Agriculture	Agricultural other	EU	PVC	0.3234	Assessment of agricultural plastics and their sustainability, 2021
Agriculture	Agricultural other	EU	PS	1.0000	Assessment of agricultural plastics and their sustainability, 2021
Agriculture	Agricultural other	EU	PP	1.0000	Assessment of agricultural plastics and their sustainability, 2021
Agriculture	Agricultural other	EU	LDPE	0.0981	Assessment of agricultural plastics and their sustainability, 2021
Agriculture	Agricultural other	EU	HDPE	0.6993	Assessment of agricultural plastics and their sustainability, 2021
Agriculture	Agricultural greenhouse films (discarded)	EU	PVC	0.0912	Assessment of agricultural plastics and their sustainability, 2021
Agriculture	Agricultural greenhouse films (discarded)	EU	LDPE	0.1568	Assessment of agricultural plastics and their sustainability, 2021

From	To	Scale	Material	Value	Source
Agriculture	Agricultural greenhouse films (in use)	EU	PVC	0.0093	Assessment of agricultural plastics and their sustainability, 2021
Agriculture	Agricultural greenhouse films (in use)	EU	LDPE	0.0159	Assessment of agricultural plastics and their sustainability, 2021
Agricultural packaging bottles	Agricultural soil (macro)	any	any	0.01600	“Ministry of Agriculture and Food - agreste - Statistics, evaluation and agricultural forecasting - Figures and data,” 2017
Agricultural packaging bottles	Collected organic waste	any	any	0.03800	See Section 7.1.8.1
Agricultural packaging films	Dumping	any	any	0.00027	See description in SI Kawecki & Nowack 2019
Agricultural packaging films	Agricultural waste collection	any	any	rest	
Agricultural packaging films	Agricultural soil (macro)	any	any	0.00000	Best case scenario
Agricultural packaging films	Agricultural soil (macro)	any	any	0.05900	“Ministry of Agriculture and Food - agreste - Statistics, evaluation and agricultural forecasting - Figures and data,” 2017
Agricultural packaging films	Collected organic waste	any	any	0.03800	See Section 7.1.8.1
Agricultural pipes	Dumping	any	any	0.00027	See description in SI Kawecki & Nowack 2019
Agricultural pipes	Agricultural waste collection	any	any	rest	
Agricultural pipes	Agricultural soil (micro)	any	any	0.00100	Assumption

From	To	Scale	Material	Value	Source
Agricultural pipes	Agricultural soil (macro)	any	any	0.00000	Best case scenario
Agricultural pipes	Agricultural soil (macro)	any	any	0.03800	“Ministry of Agriculture and Food - agreste - Statistics, evaluation and agricultural forecasting - Figures and data,” 2017
Agricultural pipes	Collected organic waste	any	any	0.03800	See Section 7.1.8.1
Agricultural plastic recycling	Secondary material reuse	any	any	rest	
Agricultural plastic recycling	Residential soil (micro)	any	any	0.000000996	EC 2023b)
Agricultural plastic recycling	Residential soil (micro)	any	any	0.0003984	
Agricultural plastic recycling	Industrial stormwater (micro)	any	any	0.000000004	EC (2023b)
Agricultural plastic recycling	Industrial stormwater (micro)	any	any	0.0000016	EC (2023b)
Agricultural plastic recycling	Incineration	any	any	0.00010	Astrup et al., 2009
Agricultural waste collection	Residential soil (macro)	any	any	0.00010	Assumption
Agricultural waste collection	Landfill	any	any	0.00000	
Agricultural waste collection	Incineration	any	any	rest	
Agricultural waste collection	Agricultural plastic recycling	any	any	0.12000	Schelker and Geisselhardt, 2011
Agricultural waste collection	Agricultural plastic recycling	any	any	0.13330	Müller, 2016
Agricultural waste collection	Agricultural plastic recycling	any	any	0.26670	Müller, 2016
Agricultural waste collection	Agricultural plastic recycling	any	any	0.20000	Schelker and Geisselhardt, 2011

8.7 Intentionally produced microparticles

Intentionally produced microparticles are used in a variety of product sectors, such as agriculture, personal care and cosmetic products (PCCP), food additives, detergents, offshore oil and gas applications and as infill on sports fields (RAC and SEAC, 2020). These microbeads are best known for their use abrasives in detergents and exfoliants, but they are also used as glitters, or to control the appearance or substance of products ("Microplastics - ECHA," n.d.).

8.7.1 European Union input data

Input data on intentionally produced microparticles per compartment for the EU was taken from RAC and SEAC (2020) (Table A24).

Table A24 EU input values for 2020 and their sources.

Compartment	Value (t)	Source	Comment
Personal Care and Cosmetic Products (PCCP)	8700	RAC and SEAC (2020)	Annex table 55
Detergents and maintenance products	16 900	RAC and SEAC (2020)	Annex table 73
Controlled release fertiliser	10 000	RAC and SEAC (2020)	Annex table 42
Fertiliser additives	4000	RAC and SEAC (2020)	Annex table 44
Plant protection products	500	RAC and SEAC (2020)	Annex table 46
Seed coating	500	RAC and SEAC (2020)	Annex table 48
In vitro diagnostic services	105.01	RAC and SEAC (2020)	Annex table 83
Medicine diffusion limitation	2300	RAC and SEAC (2020)	Annex table 96
Food additives	2300	RAC and SEAC (2020)	Not quantified, but assumed to be similar to medicine diffusion limitation.
Offshore oil & gas applications	1795	RAC and SEAC (2020)	Annex table 99
Infill material on sports fields	115 500	RAC and SEAC (2020)	Section D.13.4 in Annex XV Report (2020)
Total	162 600.01	-	-

Because input data per polymer was needed, data was collected on the mass of every polymer in tonnes per compartment. Part of this data was collected from (Scudo et al., 2017), for missing fractions assumptions were made by RIVM. From these masses per compartment and polymer, fractions of polymer content could be calculated as follows:

$$f_{polymer\ in\ compartment} = M_{polymer\ in\ compartment} / \sum M_{polymer}$$

Fractions for all polymers can be viewed in Table A25.

Table A25 Polymer fractions per compartment. For PCCP and Detergents and maintenance products data from Scudo et al. (2017) was used, other fractions are assumptions by RIVM.

Compartment	LDPE	HDPE	PP	PS	EPS	PVC	PET	Rubber	PUR	ABS	PA	PC	PMMA	Other
PCCP	0.00	0.38	0.00	0.00	0.00	0.00	0.00	0.00	0.62	0.00	0.00	0.00	0.00	0.00
Detergents and maintenance products	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.91	0.00	0.03	0.00	0.03	0.00
Controlled release fertiliser	0.10	0.10	0.10	0.00	0.00	0.10	0.00	0.00	0.10	0.00	0.10	0.00	0.10	0.30
Fertiliser additives	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Plant protection products	0.13	0.13	0.00	0.00	0.00	0.13	0.13	0.00	0.13	0.00	0.13	0.00	0.13	0.13
Seed coating	0.13	0.13	0.00	0.00	0.00	0.13	0.13	0.00	0.13	0.00	0.13	0.00	0.13	0.13
Invitro diagnostic devices	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Medicine diffusion limitation (slow release)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Food additives	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Offshore oil & gas applications	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Infill material sports fields	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00

The polymer fractions per compartment (Table A25) were multiplied by the tonnes of plastic in each compartment (Table A26). The tonnes were summed per polymer, and this resulted in the input data for the EU per polymer (Table A27)

Table A26 Input data for 2020 per polymer in the EU.

Polymer	Mass (kt)
LDPE	1.1250
HDPE	8.4170
PP	1.0000
PS	0.0000
EPS	0.0000
PVC	1.1250
PET	0.6026
Rubber	100.0000
PUR	21.9487
ABS	0.0000
PA	1.6163
PC	0.0000
PMMA	1.6026
Other	9.6628

8.7.2 *Netherlands input data*

As no specific input data was available on the use of intentionally produced microparticles in the Netherlands, the EU data was taken as a starting point. To convert these values for the Netherlands, 3 different scaling factors were applied to the data. The first factor is the fraction of the Dutch population compared to the total EU population (‘Statistics | Eurostat’, 2023). The second factor is the fraction of the Dutch value of agricultural output in 2020 compared to the EU value of agricultural output in 2020 (‘Performance of the agricultural sector’, 2023). The third factor is the value of the Dutch market share in oil and gas mining and quarrying compared to the EU market share. The scaling factor applied to the EU data was determined for each compartment (Table A27). No scaling factor was used for infill material, as data on infill consumption in 2020 in NL was found (Hoeke et al., 2024).

Table A27 NL input values for 2020.

Compartment	EU mass (t)	Scaling factor	Factor value	NL mass (t)
Personal Care and Cosmetic Products (PCCP)	8700	Population	0.039	338.44
Detergents and maintenance products	16900	Population	0.039	657.43
Controlled release fertiliser	10000	Agriculture	0.067	671.23
Fertiliser additives	4000	Agriculture	0.067	268.49
Plant protection products	500	Agriculture	0.067	33.56
Seed coating	500	Agriculture	0.067	33.56

Compartment	EU mass (t)	Scaling factor	Factor value	NL mass (t)
In vitro diagnostic services	105.01	Population	0.039	4.08
Medicine diffusion limitation	2300	Population	0.039	89.47
Food additives	2300	Population	0.039	89.47
Offshore oil & gas applications	1795	Oil-gas	0.122	219.70
Infill material on sports fields	1000000	-	-	12105
Total	147100.01	-	-	166043

8.7.3 *Transfer coefficients*

Transfer coefficients from compartment ‘Intentionally produced microparticles’ to each of the next compartments (PCCP, Detergents and maintenance products etc.) were assumed to be the same for the EU and NL.
These transfer coefficients were calculated as follows:

$$f_{to\ compartment} = M_{polymer\ in\ compartment} / \sum M_{polymer}$$

Transfer coefficients from ‘Intentionally produced microparticles’ to subsequent compartments can be found in Table A28.
Transfer coefficients from Kawecki and Nowack (2019) were used for the transfers to other compartments (Table A29).

Table A28 Transfer coefficients from ‘Intentionally produced microparticles’ to subsequent compartments for each polymer.

To compartment	**PCCP**	**Detergents and maintenance products**	**Controlled release fertiliser**	**Fertiliser additives**	**Plant protection products**	**Seed coating**	**Invitro diagnostic devices**	**Medicine diffusion limitation (slow release)**	**Food additives**	**Offshore oil & gas applications**	**Infill material sports fields**
LDPE	0.000	0.000	0.889	0.000	0.056	0.056	0.000	0.000	0.000	0.000	0.000
HDPE	0.269	0.000	0.143	0.571	0.009	0.009	0.000	0.000	0.000	0.000	0.000
PP	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
PS	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
EPS	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
PVC	0.000	0.000	0.889	0.000	0.056	0.056	0.000	0.000	0.000	0.000	0.000
PET	0.000	0.686	0.000	0.000	0.157	0.157	0.000	0.000	0.000	0.000	0.000
RUBBER	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000
PUR	0.235	0.678	0.077	0.000	0.005	0.005	0.000	0.000	0.000	0.000	0.000
ABS	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
PA	0.006	0.194	0.711	0.000	0.044	0.044	0.000	0.000	0.000	0.000	0.000
PC	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
PMMA	0.000	0.195	0.715	0.000	0.045	0.045	0.000	0.000	0.000	0.000	0.000
Other	0.002	0.000	0.385	0.000	0.008	0.008	0.008	0.169	0.169	0.252	0.000

Table A29 Other transfer coefficients. From Kawecki and Nowack (2019).

From	To	Scale	Material	Data	Source
Agricultural waste collection	Residential soil (macro)	any	any	0.00010	Assumption
Agricultural waste collection	Landfill	any	any	0.00000	
Agricultural waste collection	Incineration	any	any	rest	
Agricultural waste collection	Agricultural plastic recycling	any	any	0.12000	Schelker and Geisselhardt, 2011
Agricultural waste collection	Agricultural plastic recycling	any	any	0.13330	Müller, 2016
Agricultural waste collection	Agricultural plastic recycling	any	any	0.26670	Müller, 2016
Agricultural waste collection	Agricultural plastic recycling	any	any	0.20000	Schelker and Geisselhardt, 2011
Combined sewer overflow (micro)	Surface water (micro)	any	any	1.00000	Assumption
Controlled release fertilizser	Agricultural waste collection	any	any	0.05000	Assumption (based also on PCCP)
Controlled release fertiliser	Agricultural soil (micro)	any	any	rest	Assumption
Detergents and maintenance products	Wastewater (micro)	any	any	rest	
Detergents and maintenance products	Mixed waste collection (micro)	any	any	0.05000	Wang et al., 2016
Fertiliser additives	Agricultural waste collection	any	any	0.05000	Assumption (based also on PCCP)
Fertiliser additives	Agricultural soil (micro)	any	any	rest	Assumption
Food additives	Wastewater (micro)	any	any	rest	
Food additives	Mixed waste collection (micro)	any	any	0.05000	Wang et al., 2016
Incineration	Elimination	any	any	1.00000	
Infill material sports fields	Wastewater (micro)	any	any	0.08000	Hoeke et al. (2024)
Infill material sports fields	Residential soil (micro)	any	any	0.52000	Hoeke et al. (2024)
Infill material sports fields	Mixed waste collection (micro)	any	any	rest	Hoeke et al. (2024)

From	To	Scale	Material	Data	Source
Invitro diagnostic devices	Wastewater (micro)	any	any	rest	
Invitro diagnostic devices	Mixed waste collection (micro)	any	any	0.05000	Wang et al., 2016
Medicine diffusion limitation (slow release)	Wastewater (micro)	any	any	rest	
Medicine diffusion limitation (slow release)	Mixed waste collection (micro)	any	any	0.05000	Wang et al., 2016
Mixed waste collection (micro)	Residential soil (micro)	any	any	0.00010	Assumption
Offshore oil & gas applications	Surface water (micro)	any	any	1.00000	Assumption
On-site sewage facility (micro)	Sub-surface soil (micro)	any	any	rest	
On-site sewage facility (micro)	Sludge (micro)	any	any	0.50016	Talvitie et al., 2015
On-site sewage facility (micro)	Sludge (micro)	any	any	0.78344	Murphy et al., 2016
On-site sewage facility (micro)	Sludge (micro)	any	any	0.91509	Talvitie and Heinonen, 2014
On-site sewage facility (micro)	Sludge (micro)	any	any	0.97400	Talvitie et al., 2017
On-site sewage facility (micro)	Sludge (micro)	any	any	0.98400	Talvitie et al., 2017
On-site sewage facility (micro)	Sludge (micro)	any	any	0.68936	Ziajahromi et al., 2017
PCCP	Wastewater (micro)	any	any	rest	
PCCP	Mixed waste collection (micro)	any	any	0.05000	Wang et al., 2016
Plant protection products	Agricultural waste collection	any	any	0.05000	Assumption (based also on PCCP)
Plant protection products	Agricultural soil (micro)	any	any	rest	Assumption
Primary water treatment (micro)	Surface water (micro)	any	any	0.00000	Private communication with Frederic Guhl from FOEN
Primary water treatment (micro)	Sludge (micro)	any	any	0.50016	Talvitie et al., 2015
Primary water treatment (micro)	Sludge (micro)	any	any	0.78344	Murphy et al., 2016
Primary water treatment (micro)	Sludge (micro)	any	any	0.91509	Talvitie and Heinonen (2014)
Primary water treatment (micro)	Sludge (micro)	any	any	0.97400	Talvitie et al., 2017

From	To	Scale	Material	Data	Source
Primary water treatment (micro)	Sludge (micro)	any	any	0.98400	Talvitie et al., 2017
Primary water treatment (micro)	Sludge (micro)	any	any	0.68936	Ziajahromi et al., 2017
Primary water treatment (micro)	Secondary water treatment (micro)	any	any	rest	
Secondary water treatment (micro)	Tertiary water treatment (micro)	any	any	0.00000	Private communication with Frederic Guhl from FOEN
Secondary water treatment (micro)	Surface water (micro)	any	any	0.00000	Private communication with Frederic Guhl from FOEN
Secondary water treatment (micro)	Sludge (micro)	any	any	0.72975	Talvitie et al., 2015
Secondary water treatment (micro)	Sludge (micro)	any	any	0.07000	Talvitie et al., 2017
Secondary water treatment (micro)	Sludge (micro)	any	any	0.20000	Talvitie et al., 2017
Secondary water treatment (micro)	Sludge (micro)	any	any	0.28601	Ziajahromi et al., 2017
Secondary water treatment (micro)	Sludge (micro)	any	any	0.81000	Cabernard et al., 2016
Seed coating	Agricultural waste collection	any	any	0.05000	Assumption (based also on PCCP)
Seed coating	Agricultural soil (micro)	any	any	rest	Assumption
Sludge (micro)	Incineration	any	any	1.00000	Laube and Vonplon, 2004
Tertiary water treatment (micro)	Surface water (micro)	any	any	rest	
Tertiary water treatment (micro)	Incineration	any	any	0.83617	Talvitie et al., 2015
Tertiary water treatment (micro)	Incineration	any	any	0.97000	Mintenig et al., 2017
Tertiary water treatment (micro)	Incineration	any	any	0.00000	Talvitie et al., 2017
Tertiary water treatment (micro)	Incineration	any	any	0.61000	Cabernard et al., 2016
Tertiary water treatment (micro)	Incineration	any	any	0.39474	Ziajahromi et al., 2017
Tertiary water treatment (micro)	Incineration	any	any	1	Carr et al., 2016
Wastewater (micro)	Wastewater treatment plant (micro)	any	any	rest	

From	To	Scale	Material	Data	Source
Wastewater (micro)	Sub-surface soil (micro)	any	any	0.01000	Rutsch et al., 2006
Wastewater (micro)	Sub-surface soil (micro)	any	any	0.05000	Rutsch et al., 2006
Wastewater (micro)	Sub-surface soil (micro)	any	any	0.13000	Rutsch et al., 2006
Wastewater (micro)	Sub-surface soil (micro)	any	any	0.05000	Rutsch et al., 2006
Wastewater (micro)	Sub-surface soil (micro)	any	any	0.10000	Rutsch et al., 2006
Wastewater (micro)	On-site sewage facility (micro)	any	any	0.03000	Dominguez et al., 2016
Wastewater treatment plant (micro)	Primary water treatment (micro)	any	any	rest	
Wastewater treatment plant (micro)	Incineration	any	any	0.00000	
Wastewater treatment plant (micro)	Combined sewer overflow (micro)	any	any	0.03200	Sun et al., 2014
Wastewater treatment plant (micro)	Combined sewer overflow (micro)	any	any	0.02983	Mutzner et al., 2016

*Added by RIVM.

8.8 Packaging

Packaging refers to all plastic products “to be used for the containment, protection, handling, delivery and presentation of goods, from raw materials to processed goods, from the producer to the user or the consumer” (Eurostat, 2023a).

8.8.1 Netherlands input data

In 2020, total plastic consumption for packaging was 554 kt (Eurostat, 2023b). This number was divided into different polymer categories according to work by (Cimpan et al., 2021). Cimpan et al. divided plastic waste data for 2014 between the polymers LDPE, HDPE, PP, PS, EPS, PVC, PET and other for the EU in absolute numbers. This data was used to create a relative distribution between polymers for the packaging category (Table A30).

Table A30 Absolute numbers from Cimpan et al. (2021) and the resulting relative distribution between polymers.

Material	Final Demand	Industry Use	Total	Polymer fractions
	Waste post-consumer	Waste post-consumer		
LDPE	2885	2909	5794	0.323
HDPE	2233	1066	3299	0.184

Material	**Final Demand**	**Industry Use**	**Total**	**Polymer fractions**
	Waste post-consumer	**Waste post-consumer**		
PP	1851	1925	3776	0.211
PS	346	330	675	0.038
EPS	124	118	241	0.013
PVC	196	188	385	0.021
PET	1779	1509	3287	0.184
OTHER	201	253	455	0.025
Total	9615	8298	17 913	1.000

The fractions per polymer were then multiplied by the total plastic consumption for NL, resulting in the distribution in Table A31.

Table A31 Mass distribution of packaging plastic consumption per polymer for the Netherlands in 2020.

Material	**Consumption (kt)**
LDPE	179.21
HDPE	102.03
PP	116.78
PS	20.89
EPS	7.47
PVC	11.90
PET	101.66
OTHER	14.07

8.8.2 *EU input data*

In 2020, total plastic consumption for packaging was 15458.25 kt (Eurostat, 2023b). This total consumption was also divided between polymers using Table A13, based on work by (Cimpan et al., 2021). This resulted in the distribution in Table A32.

Table A32 Mass distribution of packaging plastic consumption per polymer for the EU in 2020.

Material	**Consumption (kt)**
LDPE	5000.36
HDPE	2846.88
PP	3258.49
PS	582.83
EPS	208.39
PVC	332.05
PET	2836.72
OTHER	392.53

8.8.3 *Transfer coefficients*

Transfer coefficients from the packaging compartment to subsequent compartments were collected from different sources (Liu and Nowack, 2022; *Plastic Packaging Composition 2011*, 2013). Other transfer coefficients from these sub compartments to other compartments were taken from several sources (Table A33).

Table A33 Transfer coefficients for packaging. All transfer coefficients were used for NL and the EU.

From	To	Material	Data	Source
Agricultural packaging bottles	Agricultural soil (macro)	any	0.01600	“Ministry of Agriculture and Food - agreste - Statistics, evaluation and agricultural forecasting - Figures and data,” (2017)
Agricultural packaging bottles	Agricultural waste collection	any	rest	
Agricultural packaging bottles	Collected organic waste	any	0.03500	See calculation in Compost section
Agricultural packaging bottles	Dumping	any	0.00027	Kawecki and Nowack (2019b)
Agricultural packaging films	Agricultural soil (macro)	any	0.05900	“Ministry of Agriculture and Food - agreste - Statistics, evaluation and agricultural forecasting - Figures and data,” (2017)
Agricultural packaging films	Agricultural waste collection	any	rest	
Agricultural packaging films	Collected organic waste	any	0.03500	See calculation in Compost section
Agricultural packaging films	Dumping	any	0.00027	Kawecki and Nowack (2019b)
Building packaging films	Construction and demolition incinerable waste collection	any	1	
Building packaging films	Dumping	any	0.00027	Kawecki and Nowack (2019b)
Building packaging films	Litter in residential environments	any	0.0013	Based on private communication with Canton of Geneva on 4/8/2019 (Kawecki and Nowack, 2021)
Building packaging films	Litter in residential environments	any	0.0147	Based on private communication with Canton of Geneva on 4/8/2020 (Kawecki and Nowack, 2021)
Consumer bags	Collected organic waste	any	0.03500	See calculation in Compost section
Consumer bags	Dumping	any	0.00027	Kawecki and Nowack (2019b)
Consumer bags	Mixed waste collection	any	rest	
Consumer bags	On-the-go consumption	LDPE	0.13950	Plastic Packaging Composition 2011 (2013)
Consumer bags	On-the-go consumption	HDPE	0.24110	Plastic Packaging Composition 2011 (2013)

From	To	Material	Data	Source
Consumer bags	On-the-go consumption	PP	0.17500	Plastic Packaging Composition 2011 (2013)
Consumer bags	On-the-go consumption	PS	0.22220	Plastic Packaging Composition 2011 (2013)
Consumer bags	On-the-go consumption	EPS	0.22220	Plastic Packaging Composition 2011 (2013)
Consumer bags	On-the-go consumption	PET	0.22220	Plastic Packaging Composition 2011 (2013)
Consumer bags	Packaging collection	any	0.00215	Schelker, Raymond, and Patrik Geisselhardt, Welche Fraktionen - Hauptkunststoffe, 2011
Consumer bottles	Collected organic waste	any	0.03500	See calculation in Compost section
Consumer bottles	Dumping	any	0.00027	Kawecki and Nowack (2019b)
Consumer bottles	Mixed waste collection	any	rest	
Consumer bottles	On-the-go consumption	PS	0.35440	Plastic Packaging Composition 2011 (2013)
Consumer bottles	On-the-go consumption	PET	0.35440	Plastic Packaging Composition 2011 (2013)
Consumer bottles	Packaging collection	LDPE	0.01075	Schelker, Raymond, and Patrik Geisselhardt, Welche Fraktionen - Hauptkunststoffe, 2011
Consumer bottles	Packaging collection	HDPE	0.53763	Schelker, Raymond, and Patrik Geisselhardt, Welche Fraktionen - Hauptkunststoffe, 2011
Consumer bottles	Packaging collection	PP	0.01075	Schelker, Raymond, and Patrik Geisselhardt, Welche Fraktionen - Hauptkunststoffe, 2011
Consumer bottles	Packaging collection	PS	0.01075	Schelker, Raymond, and Patrik Geisselhardt, Welche Fraktionen - Hauptkunststoffe, 2011
Consumer bottles	Packaging collection	EPS	0.01075	Schelker, Raymond, and Patrik Geisselhardt, Welche Fraktionen - Hauptkunststoffe, 2011
Consumer bottles	Packaging collection	PVC	0.01075	Schelker, Raymond, and Patrik Geisselhardt, Welche Fraktionen - Hauptkunststoffe, 2011
Consumer bottles	Packaging collection	PET	0.82000	Bundesamt für Umwelt, ‘Abfallmengen Und Recycling 2014 Im Überblick’, 2015
Consumer films	Collected organic waste	any	0.03500	See calculation in Compost section
Consumer films	Dumping	any	0.00027	Kawecki and Nowack (2019b)
Consumer films	Mixed waste collection	any	rest	
Consumer films	On-the-go consumption	LDPE	0.10170	Plastic Packaging Composition 2011 (2013)

From	To	Material	Data	Source
Consumer films	On-the-go consumption	HDPE	0.28570	Plastic Packaging Composition 2011 (2013)
Consumer films	On-the-go consumption	PP	0.18840	Plastic Packaging Composition 2011 (2013)
Consumer films	On-the-go consumption	PS	0.20000	Plastic Packaging Composition 2011 (2013)
Consumer films	On-the-go consumption	EPS	0.20000	Plastic Packaging Composition 2011 (2013)
Consumer films	On-the-go consumption	PVC	0.20000	Plastic Packaging Composition 2011 (2013)
Consumer films	On-the-go consumption	PET	0.20000	Plastic Packaging Composition 2011 (2013)
Non-consumer bags	Dumping	any	0.00027	Kawecki and Nowack (2019b)
Non-consumer bags	Litter in residential environments	any	0.00130	Based on private communication with Canton of Geneva on 4/8/2019
Non-consumer bags	Litter in residential environments	any	0.01470	Based on private communication with Canton of Geneva on 4/8/2020
Non-consumer bags	Mixed waste collection	any	rest	
Non-consumer bags	Packaging collection	any	0.32258	Schelker, Raymond, and Patrik Geisselhardt, Welche Fraktionen - Hauptkunststoffe, 2011
On-the-go consumption	On-the-go consumption (nature)	any	0.10456	Bundesamt für Statistik BFS. Das Kultur- Und Freizeitverhalten in Der Schweiz: Erste Ergebnisse Der Erhebung 2014; 2016.
On-the-go consumption	On-the-go consumption (residential)	any	rest	
On-the-go consumption	On-the-go consumption (transport)	any	0.25313	Based on McDonald’s Suisse, Corporate Responsibility Report 2015 McDonald’s Suisse, 2015
On-the-go consumption (nature)	Litter in natural environments	any	0.15000	Schultz, P. W.; Bator, R. J.; Large, L. B.; Bruni, C. M.; Tabanico, J. J. Littering in Context. Environ. Behav. 2013, 45 (1), 35–59.
On-the-go consumption (nature)	Mixed waste collection	any	rest	
On-the-go consumption (residential)	Litter in residential environments	any	0.50000	Private communication City of Geneva

From	To	Material	Data	Source
On-the-go consumption (residential)	Litter in residential environments	any	0.85000	Private communication City of Bern
On-the-go consumption (residential)	Mixed waste collection	any	rest	
On-the-go consumption (transport)	Litter on road sides	any	0.41463	Proportionality factor from: Schultz, P. W.; Bator, R. J.; Large, L. B.; Bruni, C. M.; Tabanico, J. J. Littering in Context. Environ. Behav. 2013, 45 (1), 35–59.
On-the-go consumption (transport)	Litter on road sides	any	0.70488	Proportionality factor from: Schultz, P. W.; Bator, R. J.; Large, L. B.; Bruni, C. M.; Tabanico, J. J. Littering in Context. Environ. Behav. 2013, 45 (1), 35–59.
On-the-go consumption (transport)	Mixed waste collection	any	rest	
Other consumer packaging	Collected organic waste	any	0.03500	See calculation in Compost section
Other consumer packaging	Dumping	any	0.00027	Kawecki and Nowack (2019b)
Other consumer packaging	Mixed waste collection	any	rest	
Other consumer packaging	On-the-go consumption	HDPE	0.11760	Plastic Packaging Composition 2011 (2013)
Other consumer packaging	On-the-go consumption	PP	0.05000	Plastic Packaging Composition 2011 (2013)
Other consumer packaging	On-the-go consumption	PS	0.05500	Plastic Packaging Composition 2011 (2013)
Other consumer packaging	On-the-go consumption	EPS	0.05500	Plastic Packaging Composition 2011 (2013)
Other consumer packaging	On-the-go consumption	PVC	0.07500	Plastic Packaging Composition 2011 (2013)
Other consumer packaging	On-the-go consumption	PET	0.08230	Plastic Packaging Composition 2011 (2013)
Other consumer packaging	Packaging collection	any	0.01075	Schelker and Geisselhardt (2011)
Other non-consumer films	Dumping	any	0.00027	Kawecki and Nowack (2019b)
Other non-consumer films	Litter in residential environments	any	0.00130	Based on private communication with Canton of Geneva on 4/8/2019
Other non-consumer films	Litter in residential environments	any	0.01470	Based on private communication with Canton of Geneva on 4/8/2020

From	To	Material	Data	Source
Other non-consumer films	Mixed waste collection	any	rest	
Other non-consumer films	Packaging collection	any	0.32258	Schelker and Geisselhardt (2011)
Other non-consumer packaging	Dumping	any	0.00027	Kawecki and Nowack (2019b)
Other non-consumer packaging	Litter in residential environments	any	0.00130	Based on private communication with Canton of Geneva on 4/8/2019
Other non-consumer packaging	Litter in residential environments	any	0.01470	Based on private communication with Canton of Geneva on 4/8/2020
Other non-consumer packaging	Mixed waste collection	any	rest	
Other non-consumer packaging	Packaging collection	LDPE	0.06452	Schelker and Geisselhardt (2011)
Other non-consumer packaging	Packaging collection	HDPE	0.06452	Schelker and Geisselhardt (2011)
Other non-consumer packaging	Packaging collection	PP	0.06452	Schelker and Geisselhardt (2011)
Other non-consumer packaging	Packaging collection	PS	0.06452	Schelker and Geisselhardt (2011)
Other non-consumer packaging	Packaging collection	EPS	0.06452	Schelker and Geisselhardt (2011)
Other non-consumer packaging	Packaging collection	PVC	0.06452	Schelker and Geisselhardt (2011)
Other non-consumer packaging	Packaging collection	PET	0.06452	Schelker and Geisselhardt (2011)
Packaging	Agricultural packaging bottles	HDPE	0.01220	Plastic Packaging Composition 2011 (2013)
Packaging	Agricultural packaging films	LDPE	0.03290	Plastic Packaging Composition 2011 (2013)
Packaging	Agricultural packaging films	PP	0.02580	Plastic Packaging Composition 2011 (2013)
Packaging	Agricultural packaging films	OTHER	0.01331	Liu and Nowack (2022); Plastic Packaging Composition 2011 (2013)
Packaging	Building packaging films	LDPE	0.01410	Plastic Packaging Composition 2011 (2013)

From	To	Material	Data	Source
Packaging	Consumer bags	LDPE	0.13480	Plastic Packaging Composition 2011 (2013)
Packaging	Consumer bags	HDPE	0.27380	Plastic Packaging Composition 2011 (2013)
Packaging	Consumer bags	PP	0.10310	Plastic Packaging Composition 2011 (2013)
Packaging	Consumer bags	PS	0.01190	Plastic Packaging Composition 2011 (2013)
Packaging	Consumer bags	PVC	0.01140	Plastic Packaging Composition 2011 (2013)
Packaging	Consumer bags	PET	0.01120	Plastic Packaging Composition 2011 (2013)
Packaging	Consumer bags	OTHER	0.12556	Liu and Nowack (2022); Plastic Packaging Composition 2011 (2013)
Packaging	Consumer bottles	LDPE	0.00160	Plastic Packaging Composition 2011 (2013)
Packaging	Consumer bottles	HDPE	0.38630	Plastic Packaging Composition 2011 (2013)
Packaging	Consumer bottles	PP	0.01030	Plastic Packaging Composition 2011 (2013)
Packaging	Consumer bottles	PVC	0.02270	Plastic Packaging Composition 2011 (2013)
Packaging	Consumer bottles	PET	0.41420	Plastic Packaging Composition 2011 (2013)
Packaging	Consumer films	LDPE	0.09250	Plastic Packaging Composition 2011 (2013)
Packaging	Consumer films	HDPE	0.06850	Plastic Packaging Composition 2011 (2013)
Packaging	Consumer films	PP	0.17780	Plastic Packaging Composition 2011 (2013)
Packaging	Consumer films	PVC	0.05680	Plastic Packaging Composition 2011 (2013)
Packaging	Consumer films	PET	0.06220	Plastic Packaging Composition 2011 (2013)
Packaging	Consumer films	OTHER	0.28529	Liu and Nowack (2022); Plastic Packaging Composition 2011 (2013)
Packaging	Non-consumer bags	LDPE	0.05330	Plastic Packaging Composition 2011 (2013)
Packaging	Non-consumer bags	PP	0.02580	Plastic Packaging Composition 2011 (2013)
Packaging	Other consumer packaging	LDPE	0.01410	Plastic Packaging Composition 2011 (2013)
Packaging	Other consumer packaging	HDPE	0.08310	Plastic Packaging Composition 2011 (2013)
Packaging	Other consumer packaging	PP	0.38140	Plastic Packaging Composition 2011 (2013)
Packaging	Other consumer packaging	PS	0.79760	Plastic Packaging Composition 2011 (2013)

From	To	Material	Data	Source
Packaging	Other consumer packaging	PVC	0.45450	Plastic Packaging Composition 2011 (2013)
Packaging	Other consumer packaging	PET	0.44280	Plastic Packaging Composition 2011 (2013)
Packaging	Other consumer packaging	OTHER	0.20724	Liu and Nowack (2022); Plastic Packaging Composition 2011 (2013)
Packaging	Other non-consumer films	LDPE	0.65670	Plastic Packaging Composition 2011 (2013)
Packaging	Other non-consumer films	HDPE	0.01220	Plastic Packaging Composition 2011 (2013)
Packaging	Other non-consumer films	PP	0.06960	Plastic Packaging Composition 2011 (2013)
Packaging	Other non-consumer films	PS	0.03570	Plastic Packaging Composition 2011 (2013)
Packaging	Other non-consumer films	PVC	0.07950	Plastic Packaging Composition 2011 (2013)
Packaging	Other non-consumer films	PET	0.01000	Plastic Packaging Composition 2011 (2013)
Packaging	Other non-consumer packaging	HDPE	0.16380	Plastic Packaging Composition 2011 (2013)
Packaging	Other non-consumer packaging	PP	0.20620	Plastic Packaging Composition 2011 (2013)
Packaging	Other non-consumer packaging	PS	0.15480	Plastic Packaging Composition 2011 (2013)
Packaging	Other non-consumer packaging	EPS	1.00000	Plastic Packaging Composition 2011 (2013)
Packaging	Other non-consumer packaging	PVC	0.37500	Plastic Packaging Composition 2011 (2013)
Packaging	Other non-consumer packaging	PET	0.05970	Plastic Packaging Composition 2011 (2013)
Packaging	Other non-consumer packaging	OTHER	0.36860	Liu and Nowack (2022); Plastic Packaging Composition 2011 (2013)
Packaging collection	Export	LDPE	0.09432	Haupt et al. (2016)
Packaging collection	Export	HDPE	0.09432	Haupt et al. (2016)
Packaging collection	Export	PP	0.09432	Haupt et al. (2016)
Packaging collection	Export	PS	0.09432	Haupt et al. (2016)
Packaging collection	Export	EPS	0.09432	Haupt et al. (2016)

From	To	Material	Data	Source
Packaging collection	Export	PVC	0.09432	Haupt et al. (2016)
Packaging collection	Export	PET	0.09432	Haupt et al. (2016)
Packaging collection	Incineration	LDPE	0.07000	Private communication PET Recycling Schweiz
Packaging collection	Incineration	HDPE	0.07000	Private communication PET Recycling Schweiz
Packaging collection	Incineration	PP	0.07000	Private communication PET Recycling Schweiz
Packaging collection	Incineration	PS	0.07000	Private communication PET Recycling Schweiz
Packaging collection	Incineration	EPS	0.07000	Private communication PET Recycling Schweiz
Packaging collection	Incineration	PVC	0.07000	Private communication PET Recycling Schweiz
Packaging collection	Incineration	PET	0.07000	Private communication PET Recycling Schweiz
Packaging collection	Residential soil (macro)	any	0.00010	Assumption
Packaging collection	Packaging recycling	any	rest	
Packaging recycling	Export	LDPE	0.16160	Haupt et al. (2016)
Packaging recycling	Export	HDPE	0.16160	Haupt et al. (2016)
Packaging recycling	Export	PP	0.16160	Haupt et al. (2016)
Packaging recycling	Export	PS	0.16160	Haupt et al. (2016)
Packaging recycling	Export	EPS	0.16160	Haupt et al. (2016)
Packaging recycling	Export	PVC	0.16160	Haupt et al. (2016)
Packaging recycling	Export	PET	0.16160	Haupt et al. (2016)
Packaging recycling	Incineration	LDPE	0.07600	Astrup et al. (2009)
Packaging recycling	Incineration	HDPE	0.07600	Astrup et al. (2009)
Packaging recycling	Incineration	PP	0.07600	Astrup et al. (2009)
Packaging recycling	Incineration	PS	0.07600	Astrup et al. (2009)
Packaging recycling	Incineration	EPS	0.07600	Astrup et al. (2009)
Packaging recycling	Incineration	PVC	0.07600	Astrup et al. (2009)
Packaging recycling	Incineration	PET	0.03000	Astrup et al. (2009)

From	To	Material	Data	Source
Packaging recycling	Industrial stormwater (micro)	any	0.000000004	Sherrington et al. (2016)
Packaging recycling	Industrial stormwater (micro)	any	0.0000016	Sherrington et al. (2016)
Packaging recycling	Residential soil (micro)	any	0.000000996	Sherrington et al. (2016)
Packaging recycling	Residential soil (micro)	any	0.0003984	Sherrington et al. (2016)
Packaging recycling	Secondary material reuse	any	rest	

8.9 Waste processes

8.9.1 Compost

Plastics can end up in organic waste produced by consumers and the agricultural sector. Organic waste is processed to compost. The mass flows and stocks of plastics in compost are modelled in a similar approach as in the PMFA model described in Kawecki and Nowack (2019) adapted to the Netherlands. Figure A7 shows the MFA related to the collection of organic waste and compost.

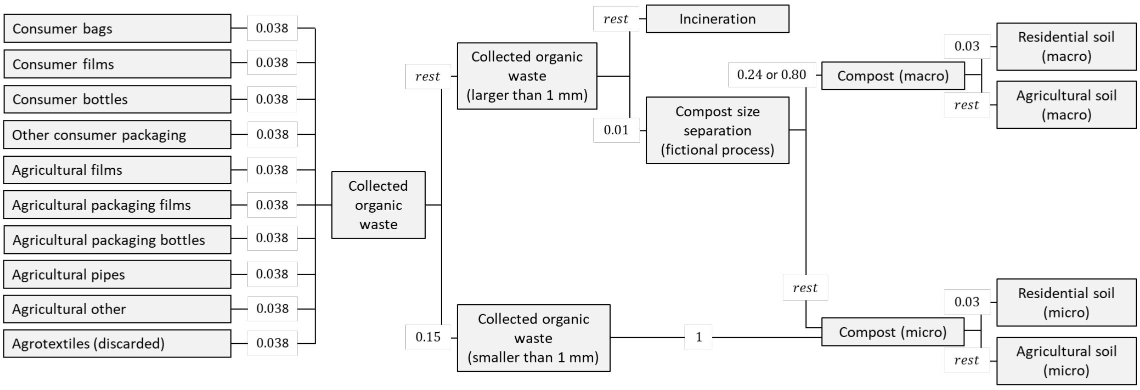

Figure A7 Flow diagram depicting the compartments and flows for compost.

The computation of the transfer coefficient (0.038 – see Figure A7) from the ten product groups to 'Collected organic waste' is explained below in Section 7.9.2.

Based on the results of the study by Faure and De Alencastro (2016), 15% of the plastic mass in collected organic waste is < 1 mm. Therefore, we added the compartments 'Collected organic waste < 1mm' and 'Collected organic waste > 1 mm' (Figure A7). The sorting process in compost plants removes 99% of the plastic pieces > 1 mm from the organic waste (Goldberg, 2018), which all goes to 'Incineration' (Figure A7). The remaining 1% of the plastic pieces > 1 mm ends up in the compost. The plastic pieces < 1 mm are too small to be sorted out. Therefore, 100% of the plastic pieces < 1 mm in organic waste end up in 'Compost (micro)' (Figure A7).

We computed both the macroplastic and microplastic mass in compost, presented by the compartments 'Compost (macro)' and 'Compost (micro)', respectively. According to the size definition that we use in our study, microplastics are < 5 mm and macroplastics > 5 mm. Therefore, the 1 mm size cut-off needs to be corrected. For this a technical component called 'Compost size separation (fictional process)' was implemented (Figure A7). Results from the study by Faure & Alencastro (2016) yielded several mass fractions of plastic pieces > 5 mm, of which we implemented the minimum (0.24) and the maximum (0.80) as transfer coefficient to 'Compost (macro)' (Figure A7) in our model. The remaining mass fraction presents plastic pieces 1 – 5 mm in size and are subsequently added to 'Compost (micro)' (Figure A7).

According to the study by Goldberg (2018), 3% of compost is applied on residential soils and the remaining 97% on agricultural soils.

8.9.2 *Transfer of microplastics to organic waste*

The sources for plastic polymers in organic waste are quite well understood, namely: Consumer bags, Consumer films, Consumer bottles, Other consumer packaging, Agricultural films, Agricultural packaging films, Agricultural bottles, Agricultural pipes, Other agricultural products, and Agrotextiles (discarded). There is currently no data available on the relative contributions of these sources. Therefore, we assumed equal contributions.

To compute the transfer coefficient from a source to 'Collected organic waste' we first executed the model without flows to 'Collected organic waste' and computed the mean mass in each of the ten source compartments. We did this for the year 2011 (results are presented in Table A34).

Next, it was assumed that the plastic mass content in collected organic waste in 2011 (15.81 kt) comes from the ten compartments listed in Table A33 and that the relative contributions of the ten compartments are equal to the mass ratios of those compartments. The mass flowing from a compartment to collected organic waste was computed by multiplying the compartments mass ratio with the total plastic mass content in 'Collected organic waste' for the year 2011, i.e. 15.81 kt.

For example, the mass outflow from 'Consumer bags' to 'Collected organic waste' was 0.1446 * 15.81 = 2.285 kt. Finally, for each of the ten compartments, the mass outflow was divided by their respective mass inflows. This yielded the transfer coefficients for the flows from each source compartment to the compartment 'Collected organic waste' (Figure A7).

Since we assumed that the relative mass inflow ratios of the ten compartments are equal to the relative outflow ratios of those compartments to collected organic waste, the transfer coefficients for all compartments are automatically the same, namely 0.038. Another way to come to this transfer coefficient is to divide the total plastic mass content in collected organic waste by the total mean mass in the ten compartments: 15.81 / 411.89 = 0.038. Although computed for the year 2011, we used this transfer coefficient for all modelled years.

Table A34 Mean masses in, and inflows to, the ten compartments that are considered a source for plastic in collected organic waste.

Compartment	**Mean mass (kt)**	**Mass ratio**	**Mean mass inflow (kt)**	**Mass outflow to organic waste (kt)**	**Transfer coefficient**
Consumer bags	59.54	0.1446	59.54	2.285	0.038
Consumer films	48.01	0.1166	48.01	1.843	0.038
Consumer bottles	68.11	0.1654	68.11	2.614	0.038
Other consumer packaging	102.85	0.2497	102.85	3.948	0.038
Agricultural films	57.49	0.1396	57.49	2.207	0.038
Agricultural packaging films	8.64	0.0210	8.64	0.331	0.038
Agricultural packaging bottles	1.11	0.0027	1.11	0.043	0.038
Agricultural pipes	19.82	0.0481	19.82	0.761	0.038
Agricultural other	16.15	0.0392	16.15	0.620	0.038
Agrotextiles (discarded)	30.17	0.0733	30.17	1.158	0.038
Sum:	**411.89**	**1**	**411.89**	**15.810**	**1**

Modelled for the year 2011. The mean masses are computed in a model run in which compost related flows were not included. The mass outflows are the masses that flow from a compartment to the compartment ‘Collected organic waste’ in the year 2011. The total plastic mass in collected organic waste in 2011 was 15.81 kt (1% of 1581 kt (Vereniging Afvalbedrijven, 2012)). The transfer coefficient belongs to the flow from the compartment to ‘Collected organic waste’ and is calculated by dividing the mass outflow by the mean mass inflow.

9 Appendix B – Model description

9.1 Details on the method

9.1.1 *Data quality indicator scores*

Data quality indicator scores (DQIS) are attributed to each input value and transfer coefficient. DQIS are used to calculate the spread around these values. The uncertainty associated with each input value is scored on 5 categories and 4 levels. The rules used to determine the scores for each category are altered from (Delphine Kawecki and Nowack, 2019b) (Table B1).

Table B1 Data quality indicator score matrix with 5 categories and 4 levels of quality.

Category	**Very good**	**Good**	**Poor**	**Very poor**
Score	DQIS = 1	DQIS = 2	DQIS = 3	DQIS = 3
Geographical representativeness	Same region (for EU: EU28 and EU28+2 qualify, for NL: CBS data qualifies)	Socioeconomically similar region (i.e. Europe vs. Switzerland)	Socioeconomically different region (i.e. USA vs. Europe)	Socioeconomically very different region (i.e. World vs. Europe)
Temporal representativeness	2019	2016-2018, 2020-2022	2009-2015, 2023-2024	Prior to 2009
Material representativeness	Same polymer	Same polymer datum corrected with data for all polymers	Data for a different polymer, or for plastic as a whole, or for similar materials	Including non-similar materials
Technical representativeness	Includes all relevant processes/flows	Includes main processes/flows	Partially including main processes/flows	Important processes/flows are missing
Source reliability	Official report/peer reviewed documentation	Market reports and other reports/public databases	Qualified estimate	Non-qualified estimate

The DQIS are used to calculate coefficients of variation (CV) using two equations, one for the reliability scores and one for the other scores (Kawecki and Nowack, 2019):

$$\mathrm{CV}rel = 1.5 \cdot e^{1.105 \cdot \mathrm{DQIS}}$$

$$\mathrm{CV}other = 1.5 \cdot e^{1.105 \cdot (\mathrm{DQIS}-1)}.$$

To calculate the total CV, the following equation is used:

$$\mathrm{CV}_{\mathrm{tot}} = \sqrt{}(\mathrm{CV}_{\mathrm{geo}}^2 + \mathrm{CV}_{\mathrm{temp}}^2 + \mathrm{CV}_{\mathrm{mat}}^2 + \mathrm{CV}_{\mathrm{tech}}^2 + \mathrm{CV}_{\mathrm{rel}}^2).$$

This $\mathrm{CV}_{\mathrm{tot}}$ is then used to create triangular or trapezoidal distribution, depending on whether 1 or 2 input values or transfer coefficients are given for the same compartment or flow. The CV determines the spread of the distribution around the given value(s) (Figure B1). The exact method of creating the distributions can be found in the SI of Kawecki and Nowack (2019).

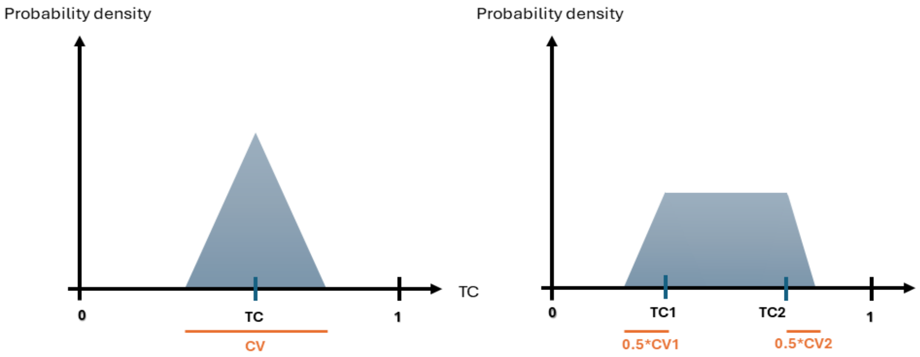

Figure B1 Example of triangular and trapezoidal distributions.

9.1.2 *Structure of the model*

The basis of the model is the code written by Bornhöft et al. (2016). They created the components.py, model.py and simulator.py scripts. In 2021, Kawecki et al. wrote additional scripts to dynamically calculate emissions specifically for plastics. We slightly adjusted some of the scripts by Kawecki et al. (2021), to better suit our purpose. For example, Kawecki et al. were mostly interested in emissions for different polymers, where for us the focus was on emissions from different product categories. In addition, we wrote the Input2csv.py script, which is used to convert the main input excel file to csv that can be used to create the databases with db_setup.py. For an overview of how the scripts relate to each other, see Figure B2. For more information on these scripts and the open model, please visit the EMPA GitHub page (empa-tsl/dpmfa (github.com), empa-tsl/plastic-dpmfa (github.com)). Our full model is available from: https://doi.org/10.5281/zenodo.12636554.

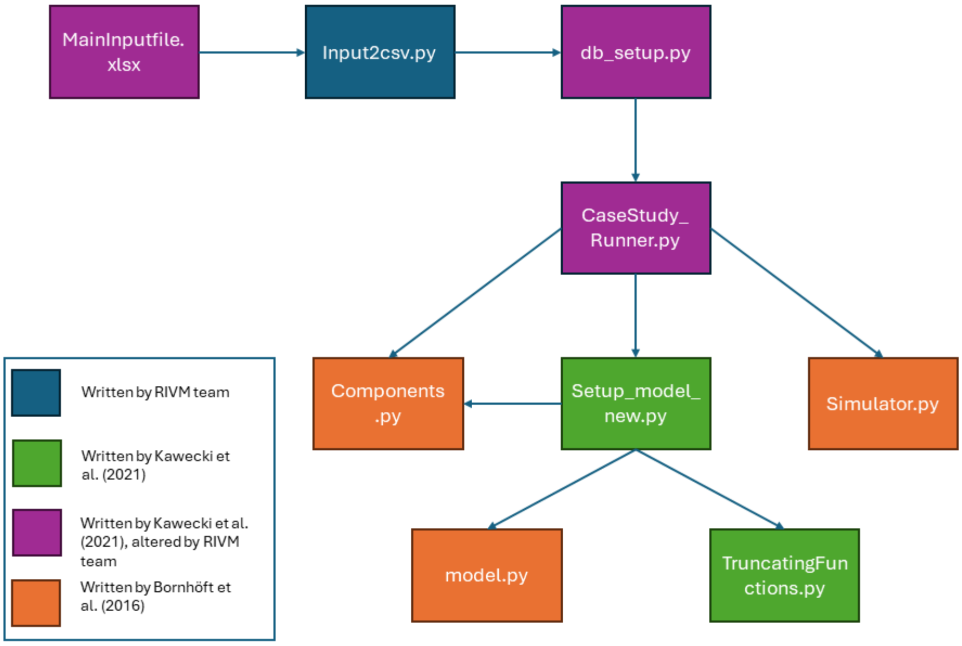

Figure B2 Overview of the model structure. Components.py, Simulator.py, and model.py are modules from the 'dpmfa' Python package.

9.1.3 *Input data*

The input data needed to run the model is collected in a file named MainInputfile.xlsx. This excel file is altered from the excel file provided and used by Kawecki et al., (2021) The main changes made in the excel file are adding a sheet with input data specifically for the Netherlands, adding categories to the input data for the EU, and adding and altering the transfer coefficients for the Netherlands in the 'Transfer coefficients' sheet. In addition, some compartments were added and removed by RIVM (for overview, see 'components' sheet in MainInputfile).

9.1.3.1 Structure of the Main_inputfile

The main input file is an excel file which contains all the collected input data needed to run the model. The file is divided into several sheets containing the different types of data. It also includes sheets containing information on the excel file and sheets that include calculations for different product categories. The sheets used as input data in the model have the following names:

- Materials
- Input_NL
- Input_EU
- Transfer coefficients
- Lifetimes_pairs
- Lifetimes
- Compartments
- Input projections

9.1.3.2 Materials

The Materials sheet has one column, containing all materials the model can be run for.

9.1.3.3 Input_NL

The Input_NL sheet includes the input data in kilotons for the Netherlands for certain compartments, years and materials. Also included are the source and the Data Quality Indicator Scores (DQIS) for the different categories (Table B2).

Table B2 Overview of columns in the Input_NL sheet of the MainInput file and their descriptions.

Column name	Description
Compartment	The compartment where the input occurs
Year	Year for which the reported input was calculated
Material	Material for which the input was reported (possible materials are presented in the 'Materials' sheet, or 'any', when the reported input is valid for any of the materials)
Data (kt)	Contains the input weight in kiloton
Source	The source of the data
Geo	DQIS score for geographical representativeness
Temp	DQIS score for temporal representativeness
Mat	DQIS score for material representativeness
Tech	DQIS score for technical completeness
Rel	DQIS score for source reliability
Spread	Is calculated from the 5 DQIS scores. In this code, the spread is the fraction of the mode that must be subtracted/added from/to the mode to obtain the minimum/maximum value of the distribution.
Codes and comments	Optional extra comments on the data

9.1.3.4 Input_EU

The Input_EU sheet includes the input data in kiloton for the European Union including Switzerland and Norway for certain compartments, years and materials. For further information see paragraph 2.2.

9.1.3.5 Transfer coefficients

This sheet includes the transfer coefficients (TCs) for each relevant compartment combination.

Table B3 Overview of columns in the Transfer_coefficients sheet of the MainInput file and their descriptions.

Column name	Description
From	The compartment from which the material flows
To	The compartment to which the material flows
Scale	Scale of the TC; either NL or EU
Material	The material for which the TC is relevant
Data	The transfer coefficient; fraction of the material in the 'From' compartment that is transferred to the 'To' compartment.
Priority	Ensure the total TC values in a compartment equal 1. If not, the model adjusts TC values based on priority. The TC with the highest priority remains unchanged and the one with the lower priority is adjusted to reach a sum of 1 with the other TC.
Source	The source of the data
Geo NL	DQIS score for geographical representativeness (filled if the Scale is NL)
Geo EU	DQIS score for geographical representativeness (filled if the Scale is EU)
Temp	DQIS score for temporal representativeness
Mat	DQIS score for material representativeness
Tech	DQIS score for technical completeness
Rel	DQIS score for source reliability
Spread	Is calculated from the 5 DQIS scores. In this code, the spread is the fraction of the mode that must be subtracted/added from/to the mode to obtain the minimum/maximum value of the distribution.
Comments	Optional extra comments on the data

9.1.3.6 Lifetimes_pairs

This sheet contains two columns, named 'Stock compartments' and 'Lifetime category'. The first column contains names of compartments with lifetimes as in the 'Transfer coefficients sheet'. The second column specifies which lifetime should be taken from the 'Lifetimes' sheet for each compartment.

9.1.3.7 Lifetimes

This sheet was copied from Kawecki et al. (2021). Each column in this sheet represents a compartment in which the material has a residence time. Each row represents a year, and each cell contains a fraction.
Year 0 represents the year the input was given to the compartment. The fraction corresponding to year 0 represents the fraction of material that is released to the next compartment in the same year as the input was given to the compartment. The fractions in other years represent the fraction of the input released a certain number of years after the input was given to the compartment. The fractions in every column should add up to 1, so that 100% of the material in the compartment is emitted after the lifetime ends.

9.1.3.8 Compartments

This sheet contains the names of all compartments, and whether each compartment is a stock, flow or sink (Table B4).

Table B4 Overview of columns in the Compartments sheet of the MainInput file and their descriptions.

Column name	Description
Fullabel	Compartment name (as in Input_NL, Input_EU and Transfer coefficients sheets)
Type	The type of compartment: Stock, Flow or Sink
Name	Compartment name without spaces
Adopted from Kawecki & Nowack (2019) or added	Source of the compartment information: adopted from Kawecki & Nowack or added by RIVM team.

9.1.4 Scripts written by RIVM team

To make the model work for the purpose of this project, the config.py and input2csv.py files were written. The former is a file where values for variables can be selected to be used in the model, such as the start year, end year, number of runs and the region (NL or EU). More information on these input variables can be found in Appendix 7.1.
The input2csv.py script was created to make 5 separate input csv files from the Main_InputFile.xlsx data (Compartments, Materials, Lifetimes, Input and Transfer coefficients). These CSV files have to be created in a certain way, so that later a SQL database with a specific structure could be created.

9.1.4.1 Input2csv

Firstly, the compartments, materials and lifetimes sheets are read from the MainInput_file. No large changes are made to this data.

9.1.4.2 Input

To prepare for the Input csv, firstly the Input_NL or Input_EU sheet is selected based on the choice made in config.py. If no input value is present in the start year (specified in config.py), the start year is given an input of 0. All rows are repeated for all years between startyear and endyear. Values are filled through linear interpolation. If extrapolation is needed, fractions from the 'Input projections' (OECD, 2022). Using these fractions, extrapolation until 2060 is possible. The code ensures that a maximum of 2 input values is present for each combination of compartment, material and year. Finally, DQIS for temporal representativeness are filled according to Table B1.

9.1.4.3 Transfer coefficients

The 'Transfer coefficients' sheet is loaded from the MainInputfile, and only the TCs for the chosen region are selected. The rows containing 'rest' TCs are separated from the other TCs, and are given DQIS of 0 for all categories. Consequently, if more than 2 TCs are given for the same from compartment, to compartment and material combination, the lowest and highest TCs are selected. All rows are repeated for all years between start year and end year. Finally, the DQIS for temporal representativeness are filled according to Table B1.

9.2 Dependencies

The model was run using Python version 3.11.7. In addition, the following packages are required:

- Numpy (version 1.26.4)
- Pandas (version 2.1.4)
- Dpmfa (version 1.1).
- Sqlite (version 3.41.2)

9.3 Variables in config.py

The script config.py lets the user define model parameters. Descriptions of the parameters can be found in Table B5.

Table B5 Parameters to be defined by the user in config.py.

Variable name	Description
Inputfile	Name of the inputfile
Input_distr	Type of distribution used for the input values
OS_env	Type of operating system: windows or linux
Region	Region the model is run for: NL or EU
Endyear	End year of the period the model is run for
Startyear	Start year of the period the model is run for
Speriod	Special period for detailed output printing
RUNS	Number of runs for the Monte Carlo simulations

10 Appendix C – Mitigation measures

10.1 Solution-focussed sustainability assessment approach

In order to inform on the effectiveness of mitigation measures we have combined insight from data and literature sources with insights from practice. This helps cope with the numerous sources of microplastics to the environment, various possible measures to mitigate their emission to the environment, and uncertainty over the effectiveness of the measures. This approach is in line with Solution-focussed Sustainability assessment (Figure C1), which supports stakeholder and science supported solutions for complex problems such as reducing microplastic emissions (Zijp et al., 2016). The approach originates from risk assessment studies to improve the utility of risk assessment by focussing on solutions instead of risks and it can be extended to sustainability assessment. In this report we follow the iterative steps of solution-focussed assessments, which includes stakeholders, in this study limited to experts on microplastic solutions upfront in the analysis to ensure that the solutions explored are found important by experts. In this case the solutions are the most effective and feasible measures for reducing microplastic emissions. To ensure the measures for which calculation has been done are those that are supported by and seen as promising by experts, the main sources and possible measures were identified and scored in a participatory manner. As argued by Pahl and Wales (2017), environmental microplastics are also an issue caused by humans and thus social sciences and qualitative approaches are helpful to provide new insights to also take into account human perception and behaviour. Social research that further takes into account social factors of microplastic emission and effective measures is in its infancy and can benefit from further development.

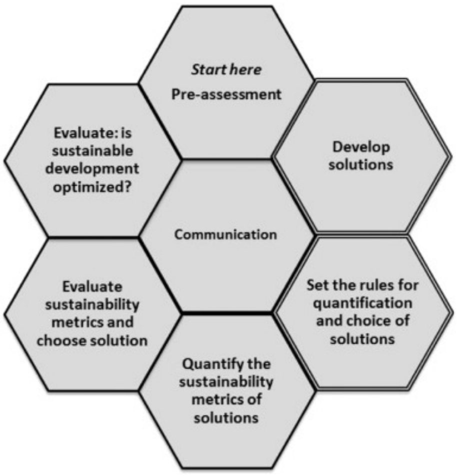

Figure C1 Process of solution-focussed sustainability assessment (source: (Zijp et al., 2016)).

In this report the solutions or measures identified are also quantified using the modelling, and the next step would be to discuss the quantification with the experts and then to choose measures or solutions based on this discussion. This is however left out of the scope of the current study within the constraints of time and resources.

10.2 Expert mapping

To include the relevant stakeholders in the workshop, a stakeholder mapping was conducted for the scope of the research. Thus stakeholders were included for the Dutch and European context and covering the expertise of different microplastics sources. A list was composed that was reviewed by several RIVM experts in the field to compile a complete list of relevant experts. Below is a table of the relevant organisations and experts that participated in the workshop.

Table C1 Overview of organisations and participants of participatory workshop

Organisation	**Country**	**Name**	**Participated in workshop**	**Signed Conflict of Interest form**
PEW	EU	Isabel Jarrett, Leah Segui	Yes	Yes
Rijkswaterstaat	NL	Ageeth Boos, Mireille Reijme	Yes	Yes
OVAM	BE	Anne-Marie Prins	Yes	Yes
University of Amsterdam	NL	Antonia Praetorius	Yes	Yes
Fraunhofer Instituut	DE	Ilka Gehrke; Daniel Maga	Yes	Yes
University of Leiden	NL	Esther Kentin	Yes	Yes
Deltares	NL	Petra Krystek; F.M. Kleissen, Joana Mira Veiga	Yes	Yes
Milieu Centraal	NL	Judth Brouwer, Kiki Dehmers	Yes	Yes
VITO	BE	Leen van Esch, Annelies Scholaert	Yes	Yes
Norwegian University of Science and Technology	NO	Martin Wagner	Yes	Yes
Ministry of I&W	NL	Nina Langen; Leander Mastenbroek	Yes	Yes
Open University	NL	Sya Hoeke	Yes	Yes
TNO	NL	Tim Bulters, Anna Schwarz	Yes	Yes
Plastic Soup Foundation	NL	Harmen Spek	Yes	Yes
Vlaamse Milieu Maatschappij	BE	Maarten de Jonge	Yes	Yes
University of Bayreuth (Limnopplast)	EU	Martin Löder	Yes	Yes
RIVM	NL	Melvin Faber, Elias de Valk, Joris Quik, Anne van Bruggen, Yvette Mellink	Yes	Yes

The following organisations were also invited to participate, but could not do so for various reasons:

- University of Amsterdam, Annemarie van Wezel
- Wageningen University
- The Ocean Cleanup
- Earth Action
- CE Delft
- University of Groningen
- Ramboll Sweden
- Nano consult
- Utrecht University
- Royal Haskoning
- Arcadis
- Eunomia
- Regional water authorities Netherlands; Vallei en Veluwe
- Food and Agriculture Organization of the United Nations (FAO)

During the workshop, the experts indicated to have the following expertise based on microplastic sources:

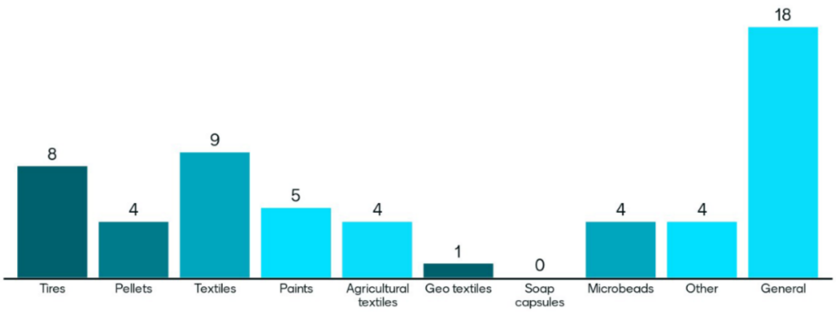

Figure C2 Workshop attendee expertise related to various microplastic sources.

10.2.1 *Conflict of Interest Form*

All participants in the workshop were asked to sign the following conflict of interest form.

Conflict of Interest Statement Expert workshop on prioritising and quantifying microplastics measures

Conflict of interest exists when a participant (or a member of their immediate family (parent, spouse, child, or sibling)) has financial or personal relationships that inappropriately influence (bias) his or her actions.

As a participant of Expert workshop on prioritising and quantifying microplastics measures, I declare the following:

I. I hereby agrees to treat all discussions within the Expert workshop on prioritising and quantifying microplastics measures as confidential.

II. I realise that in absolutely no way at all may there be any conflict of interest. I confirm that neither I nor any of my relatives nor any business with which I am associated have any personal or business interest in or potential for personal gain from any of the organisations or projects linked to the Expert workshop on prioritising and quantifying microplastics measures.

III. Hereby confirms that I will duly report any new interests that should arise in the interim, the termination of any existing interests, changes to existing interests or interests that will become more relevant over the course of the process.

Name and title:

Organisation:

Signature:

Date:

10.3 Mitigation measures per source as derived from literature and workshop

10.3.1 Pre-production pellets

Table C2 Prioritization of measures by workshop participants by scoring on feasibility (1-Easy to 3-Difficult) and effectiveness (1-High effectiveness to 3-Low effectiveness)

Measure description	Average of feasibility and effectiveness scores	Average feasibility score	Average effectiveness score	Number of experts that scored these measures
Mandatory requirements (e.g. through a permit or a certification scheme in a new EU law)	1.44	1.67	1.22	9
Improve packaging for transport of pellets	1.57	1.43	1.71	7
Require all containers and packaging material for pellet transports are airtight and puncture resistant	1.73	1.80	1.67	5
Upgraded voluntary agreement with effective Commission involvement to reduce pellet spills and losses and to increase the effectiveness of measures taken and reported.	1.79	1.29	2.29	7
Pellet loss reduction targets	1.81	1.63	2.00	8
Classify pellets as harmful in international maritime law	1.81	2.00	1.63	8
Mandatory reporting of containers lost at sea	1.88	1.63	2.13	8
Develop an EPR systems for the entire value chain	1.90	2.00	1.80	5
Standardised methodology to measure pellet losses	2.36	2.00	2.71	7

10.3.2 Tyre wear

Table C3 Prioritization of measures by workshop participants by scoring on feasibility (1-Easy to 3-Difficult) and effectiveness (1-High effectiveness to 3-Low effectiveness)

Measure description	Average of feasibility and effectiveness scores	Average feasibility score	Average effectiveness score	Number of experts that scored these measures
Reduction of maximum speed	1.50	1.33	1.67	6
Street cleaning in urban areas	1.58	1.33	1.83	6
Improve capturing of road runoff	1.60	1.80	1.40	5
Road pricing	1.67	1.33	2.00	3
TPMS for old cars (>4 years) plus test method	1.67	1.67	1.67	3
Make public transport more attractive	1.70	2.00	1.40	5
Implement technologies that capture tyre wear at the source	1.75	2.50	1.00	3
Ban on winter tyres in summer	1.83	1.83	2.00	6
Abrasion rate criteria to be added to road design requirements & road material characteristics (porous asphalt / rubber asphalt)	1.94	2.13	1.75	4
Legal threshold for tyre wear	2.00	2.50	1.50	8
Tyre label integrated into energy label plus est method	2.00	1.80	2.20	5
Education	2.00	1.33	2.67	3

Measure description	Average of feasibility and effectiveness scores	Average feasibility score	Average effectiveness score	Number of experts that scored these measures
Promotion of artificial intelligence and autonomous driving to reduce abrasion	2.53	2.80	2.25	4
Legal threshold road wear	2.78	2.80	2.75	4

10.3.3 Paints and coatings

Table C4 Prioritization of measures by workshop participants by scoring on feasibility (1-Easy to 3-Difficult) and effectiveness (1-High effectiveness to 3-Low effectiveness)

Measure description	Average of feasibility and effectiveness scores	Average feasibility score	Average effectiveness score	Number of experts that scored these measures
Using methods that limit the spreading of dust during the removal of coatings	1.63	1.50	1.75	4
Research budget for MP from paint	1.63	1.00	2.25	4
Replacement of older sanders	1.67	1.00	2.33	3
Develop new paint products: mineral-based, powder, self-healing, biodegradable polymers	1.90	2.20	1.60	5
Waste Management: Re-use and recycling of leftover paints	2.00	1.50	2.50	2
Paint innovation: Improving the wear resistance of the paint; replacing persistent synthetic polymers with more environment friendly ingredients;	2.13	3.00	1.25	4

Measure description	Average of feasibility and effectiveness scores	Average feasibility score	Average effectiveness score	Number of experts that scored these measures
developing products (catalysts) that enhance the degradation of paint at end-of-life.				
Reducing the wear of coatings: Improving the wear resistance of the paint itself (paint innovation); improving the method of paint application, especially for DIY. Pre-treatment of the surface that needs to be painted (sanding and priming) can prevent untimely wear; improving the lifespan of the paint by cleaning; timely maintenance of the paint (before the layer starts peeling).	2.17	3.00	1.33	3
Brush rinsing awareness campaign; Preventing the rinsing of brushes and rollers in the sink	2.17	1.83	2.50	6
Waste Management: Recycling of end-of-life paint residues	2.25	2.00	2.50	2
Legal warranty period for paint	2.25	1.75	2.75	4
Reduction emissions from recreational boats	2.50	3.00	2.00	2
Reducing the amount of paint used e.g. through use of equipment, using other materials	2.50	3.00	2.00	4

10.3.4 Textiles

Table C5 Prioritization of measures by workshop participants by scoring on feasibility (1-Easy to 3-Difficult) and effectiveness (1-High effectiveness to 3-Low effectiveness)

Measure description	Average of feasibility and effectiveness scores	Average feasibility score	Average effectiveness score	Number of experts that scored these measures
Reducing synthetic textiles, fleece, glitter	1.79	2.50	1.08	12
Not only the clothes we use but also curtains, carpets, furniture, etc. We need policies and economic instruments at the level of design and production	1.83	1.67	2.00	3
Placing microplastic filters in washing machines	1.88	1.92	1.85	13
Design and production principles for synthetic textiles	1.91	2.18	1.64	11
Regulations for washing machines and filters in EU Ecodesign and IMVO Covenant	1.95	1.82	2.09	11
Add steps to waste water purification guidelines using other techniques	2.00	2.33	1.67	9
Improve removal from WWTPs	2.00	2.00	2.00	5
Apply natural fibres	2.00	2.00	2.00	9
Other measures to reduce emission to waste water	2.00	2.00	2.00	2
Change washing instructions: use liquid detergent, wash at low temperature and not too often	2.00	1.55	2.45	11

Measure description	**Average of feasibility and effectiveness scores**	**Average feasibility score**	**Average effectiveness score**	**Number of experts that scored these measures**
Awareness among consumers - buy higher quality, prevent waste (from cheap fashion)	2.02	1.70	2.33	9
Informing consumers on MP reduction through washing	2.05	1.36	2.73	11
Add guidance on washing machines and dryers to not wash filters	2.33	1.67	3.00	9
End fast fashion	2.36	2.86	1.86	7
Enable consumers to make sustainable choices	2.40	2.10	2.70	10
Apply finishings and coatings that reduce fiber loss	2.45	2.30	2.60	10

10.3.5 *Agriculture*

Table C6 Prioritization of measures by workshop participants by scoring on feasibility (1-Easy to 3-Difficult) and effectiveness (1-High effectiveness to 3-Low effectiveness)

Measure description	**Average of feasibility and effectiveness scores**	**Average feasibility score**	**Average effectiveness score**	**Number of experts that scored these measures**
Deposit return scheme to encourage reuse and recovery	1.50	1.83	1.17	6
Promote durable solutions instead of easy to tear materials	1.50	1.80	1.20	5
Use less biodegradable (i.e. long-lasting) films, more resistant to UV- and	1.67	1.33	2.00	6

Measure description	**Average of feasibility and effectiveness scores**	**Average feasibility score**	**Average effectiveness score**	**Number of experts that scored these measures**
biodegradation to minimise MP release and encourage use over multiple season				
essential use -> what is the exact use per sector. E.g. to reduce weeds, you can also use mechanical methods (but avoid regrettable substitution)	1.70	2.00	1.40	5
Promote alternatives and eco-friendly materials (natural fibres and biodegradable polymers)	1.80	2.20	1.40	5
Recovery of agricultural foil	1.83	2.00	1.67	6
Stimulate that it is recovered (e.g. pay for weight that is lost)	1.86	2.29	1.43	7
Regulate the type of fibre or polymer used	1.88	2.17	1.60	5
collect more knowledge on use within sectors of agriculture, algicultural methods etc.	1.90	1.40	2.40	5
Redesign to make reusable - not digging them in the soil	1.90	2.20	1.60	5
Secure an adequate maintenance and the use of toxic free agricultural plastics	2.00	2.00	2.00	5
Use biodegradable mulch films (only in the case if the mulch fimls could not be removed)	2.00	1.83	2.17	6
Reduce food waste --> less agriculture necessary and thus less plastic	2.08	2.33	1.83	6
Cost:benefit analyses required (water savings vs MP/chem release)	2.20	1.60	2.80	5

Measure description	Average of feasibility and effectiveness scores	Average feasibility score	Average effectiveness score	Number of experts that scored these measures
Understand the release of MPs from biofilms also in relation to sludge that is possible applied to agricultural lands	2.25	2.50	2.00	2
Apply recycled content	2.25	1.67	2.83	6
Use good degradable foils	2.50	2.50	2.50	4

10.3.6 Macroplastics

Table C7 Prioritization of measures by workshop participants by scoring on feasibility (1-Easy to 3-Difficult) and effectiveness (1-High effectiveness to 3-Low effectiveness)

Measure description	Average of feasibility and effectiveness scores	Average feasibility score	Average effectiveness score	Number of experts that scored these measures
Further restrict single-use disposable plastic packaging and items	1.44	1.78	1.11	9
Capture MP at production and recycling plants	1.44	1.33	1.56	9
Improved packaging concepts	1.45	1.80	1.10	10
Restrict non-essential plastic products	1.45	1.80	1.10	10
Restrict single use plastics	1.45	1.82	1.09	11
Refuse and reduce plastic product use	1.61	2.11	1.11	9
Slow down product life cycles - reuse, repair etc.	1.67	2.11	1.22	9
Ban EPS in packaging	1.70	1.90	1.50	10

Measure description	**Average of feasibility and effectiveness scores**	**Average feasibility score**	**Average effectiveness score**	**Number of experts that scored these measures**
Incentives for re-use and innovative design that leads to less plastic waste generated	1.72	1.67	1.78	9
Litter clean-up (roadsides, parks, woodlands)	1.75	1.50	2.00	10
return systems, incentives / Increase deposit systems (e.g. to pet trays)	1.78	1.89	1.67	9
Wider rollout of deposit system	1.83	2.33	1.33	9
true pricing for virgin plastic	2.00	2.00	2.00	2
reduce material complexity to reach more true circularity	2.06	2.67	1.44	9
Proper waste management systems / Improved waste management/behaviour to minimise mismanagement	2.06	2.22	1.89	9
Ocean / river clean-up	2.25	2.10	2.40	10
Phase down production of virgin plastics	2.31	2.63	2.00	8
Redesign polymers to minimise shedding of MP	2.36	2.71	2.00	7
Extraction of plastics from landfills	2.60	2.80	2.40	10
self-healing plastics, if feasible. Currently researched by WUR student (article in Wageningen World)	2.75	3.00	2.50	6

10.3.7 Soap capsules

Table C8 Prioritization of measures by workshop participants by scoring on feasibility (1-Easy to 3-Difficult) and effectiveness (1-High effectiveness to 3-Low effectiveness)

Measure description	Average of feasibility and effectiveness scores	Average feasibility score	Average effectiveness score	Number of experts that scored these measures
Change product to reduce use of soluble polymers / films (e.g. Use solid tablets instead (as in the old days) or use washing powder)	1.31	1.40	1.22	9
Restriction of non-biodegradable water-soluble capsule shells (So no non-biodegradable shells, whether they are plastic or not)	1.45	1.73	1.18	11
Using casein, a milk protein, as a polymeric film which is water-soluble and biodegradable	1.50	1.67	1.33	9
restriction on basis of non-essential use (ban)	1.80	2.50	1.10	10
Extended producer responsibility	1.95	2.00	1.90	10
Definition/categorisation (Do we consider these as Mps? Or as polymers?)	2.00	2.00	2.00	2
arise consumer awareness	2.00	1.64	2.36	11
Create standards for determining water solubility and degradability	2.28	2.67	1.89	9
Integrative analysis e.g. (Connect use of of capsules to a lot of water use --> consumer behaviour to use the dishwasher less)	2.50	2.33	2.67	9
Base on existing knowledge on polymers to assess How bad is this? if it is biodegradable?	2.67	3.00	2.33	3

Measure description	Average of feasibility and effectiveness scores	Average feasibility score	Average effectiveness score	Number of experts that scored these measures
we do not even know what polymers are used/allowed				

10.3.8 Geotextiles

Table C9 Prioritization of measures by workshop participants by scoring on feasibility (1-Easy to 3-Difficult) and effectiveness (1-High effectiveness to 3-Low effectiveness)

Measure description	Average of feasibility and effectiveness scores	Average feasibility score	Average effectiveness score	Number of experts that scored these measures
oblige, promote alternatives and eco-friendly materials (natural fibres and biodegradable polymers)	1.67	2.17	1.17	6
Use natural fibres or geotextiles that degrade after the intended life time	1.67	1.67	1.67	6
Use of natural fibres	1.79	2.57	1.00	7
Regulate the range of applications (e.g. hydraulic application)	2.00	2.00	2.00	6
Determine if use of geotextiles is indeed essential (textiles, not films)	2.00	2.00	2.00	4
Regulate the type of fibre or polymer used	2.08	2.17	2.00	6
Stimulate that it is recovered (e.g. pay for weight that is lost)	2.08	2.50	1.67	6

Apply recycled content and assess effect of additive chemicals as well as replacements. Recycled 'quality' might shed even more MPs	2.33	2.00	2.67	6
Secure an adequate maintenance and the use of toxic free geotextiles.	2.50	2.50	2.50	6
provide a register of all used geotextiles in works, so that it also can be removed if necessary	2.50	2.33	2.67	6
presence of UV or no UV for degradation	3.00	3.00	3.00	3

10.4 Detailed table on alterations made for each mitigation measure

All transfer coefficients are altered for scale NL, and are the same for any material.

Table C10 Detailed alterations made for every mitigation measure.

Measure ID	**Source**	**Type of alteration**	**Change**	**From compartment**	**To compartment**	**Old value**	**New value**
1	**Pellets**	Transfer coefficients	Decrease TC with 30%	Transport of primary plastics	Pellet losses transport land	1.00E-06	7.00E-07
1	**Pellets**	Transfer coefficients	Decrease TC with 30%	Transport of primary plastics	Pellet losses transport land	4.56E-04	3.19E-04
1	**Pellets**	Transfer coefficients	Decrease TC with 30%	Transport of primary plastics	Sea water (micro)	1.00E-06	7.00E-07
1	**Pellets**	Transfer coefficients	Decrease TC with 30%	Transport of primary plastics	Sea water (micro)	4.40E-05	3.08E-05
2	**Pellets**	Transfer coefficients	Decrease TC with 30%	Pellet conversion	Pellet losses industrial plants	1.00E-06	7.00E-07
2	**Pellets**	Transfer coefficients	Decrease TC with 30%	Pellet conversion	Pellet losses industrial plants	4.00E-04	2.80E-04
2	**Pellets**	Transfer coefficients	Decrease TC with 30%	Domestic primary plastic production	Pellet losses industrial plants	1.00E-06	7.00E-07
2	**Pellets**	Transfer coefficients	Decrease TC with 30%	Domestic primary plastic production	Pellet losses industrial plants	4.00E-04	2.80E-04

Measure ID	Source	Type of alteration	Change	From compartment	To compartment	Old value	New value
3	**Pellets**	Transfer coefficients	reduce 30% and add flow to incineration	Industrial stormwater (micro)	Wastewater treatment plant (micro)	6.00E-01	4.20E-01
3	**Pellets**	Transfer coefficients	leave the same	Industrial stormwater (micro)	Residential soil (micro)	3.00E-01	3.00E-01
3	**Pellets**	Transfer coefficients	reduce 30% and add flow to incineration	Industrial stormwater (micro)	Surface water (micro)	1.00E-01	7.00E-02
3	**Pellets**	Transfer coefficients	Add elimintation route	Industrial stormwater (micro)	Incineration	0.00E+00	rest
4	**Tyre wear**	Input	Lower input values with 30%	Tyre wear			
5	**Tyre wear**	Transfer coefficients	Decrease with 30%	Highway DAB non cleaned	Road side soil (micro)	9.00E-01	6.30E-01
5	**Tyre wear**	Transfer coefficients	Decrease with 30%	Highway DAB non cleaned	Surface water (micro)	1.00E-01	7.00E-02
5	**Tyre wear**	Transfer coefficients	New flow	Highway DAB non cleaned	Wastewater (micro)		rest
5	**Tyre wear**	Transfer coefficients					
5	**Tyre wear**	Transfer coefficients	Decrease with 30%	Highway ZOAB non cleaned	Road side soil (micro)	9.00E-01	6.30E-01
5	**Tyre wear**	Transfer coefficients	Decrease with 30%	Highway ZOAB non cleaned	Surface water (micro)	1.00E-01	7.00E-02
5	**Tyre wear**	Transfer coefficients	New flow	Highway ZOAB non cleaned	Wastewater (micro)		rest
5	**Tyre wear**	Transfer coefficients					
5	**Tyre wear**	Transfer coefficients	No change	Rural roads	Road cleaning	1.00E-02	1.00E-02
5	**Tyre wear**	Transfer coefficients	No change	Rural roads	Road cleaning	2.00E-02	2.00E-02
5	**Tyre wear**	Transfer coefficients	Decrease with 30%	Rural roads	Outdoor air (micro)	5.00E-02	3.50E-02

Measure ID	Source	Type of alteration	Change	From compartment	To compartment	Old value	New value
5	**Tyre wear**	Transfer coefficients	Decrease with 30%	Rural roads	Outdoor air (micro)	1.00E-01	7.00E-02
5	**Tyre wear**	Transfer coefficients	Decrease with 30%	Rural roads	Road side soil (micro)	9.00E-01	6.30E-01
5	**Tyre wear**	Transfer coefficients	Decrease with 30%	Rural roads	Surface water (micro)	1.00E-01	7.00E-02
5	**Tyre wear**	Transfer coefficients	New flow	Rural roads	Wastewater (micro)		rest
5	**Tyre wear**	Transfer coefficients					
5	**Tyre wear**	Transfer coefficients	No change	Urban roads	Road cleaning	1.00E-01	1.00E-01
5	**Tyre wear**	Transfer coefficients	No change	Urban roads	Road cleaning	2.00E-02	2.00E-02
5	**Tyre wear**	Transfer coefficients	No change	Urban roads	Road runoff	rest	
5	**Tyre wear**	Transfer coefficients	Decrease with 30%	Urban roads	Outdoor air (micro)	5.00E-02	3.50E-02
5	**Tyre wear**	Transfer coefficients	Decrease with 30%	Urban roads	Outdoor air (micro)	1.00E-01	7.00E-02
5	**Tyre wear**	Transfer coefficients	Decrease with 30%	Urban roads	Road side soil (micro)	4.00E-01	2.80E-01
5	**Tyre wear**	Transfer coefficients					
5	**Tyre wear**	Transfer coefficients	No change	Road runoff	Road side soil (micro)	rest	
5	**Tyre wear**	Transfer coefficients	No change	Road runoff	Stormwater (micro)	1.79E-01	
5	**Tyre wear**	Transfer coefficients	No change	Road runoff	Surface water (micro)	2.55E-01	
5	**Tyre wear**	Transfer coefficients	No change	Road runoff	Wastewater (micro)	3.47E-01	
6	**Tyre wear**	Transfer coefficients	No change	Highway DAB	Highway DAB non cleaned	rest	rest
6	**Tyre wear**	Transfer coefficients	No change	Highway DAB	Outdoor air (micro)	5.00E-02	5.00E-02
6	**Tyre wear**	Transfer coefficients	No change	Highway DAB	Outdoor air (micro)	1.00E-01	1.00E-01

Measure ID	Source	Type of alteration	Change	From compartment	To compartment	Old value	New value
6	**Tyre wear**	Transfer coefficients	Increase with 30%	Highway DAB	Road cleaning	1.00E-02	1.30E-02
6	**Tyre wear**	Transfer coefficients	Increase with 30%	Highway DAB	Road cleaning	2.00E-02	2.60E-02
6	**Tyre wear**	Transfer coefficients	No change	Highway ZOAB	Highway ZOAB non cleaned	rest	rest
6	**Tyre wear**	Transfer coefficients	No change	Highway ZOAB	Outdoor air (micro)	5.00E-02	5.00E-02
6	**Tyre wear**	Transfer coefficients	No change	Highway ZOAB	Outdoor air (micro)	1.00E-01	1.00E-01
6	**Tyre wear**	Transfer coefficients	Increase with 30%, to max 0.9	Highway ZOAB	Road cleaning	8.00E-01	9.00E-01
6	**Tyre wear**	Transfer coefficients	Increase with 30%, to max 1	Highway ZOAB	Road cleaning	9.00E-01	1.00E+00
6	**Tyre wear**	Transfer coefficients	No change	Rural roads	Outdoor air (micro)	5.00E-02	5.00E-02
6	**Tyre wear**	Transfer coefficients	No change	Rural roads	Outdoor air (micro)	1.00E-01	1.00E-01
6	**Tyre wear**	Transfer coefficients	Increase with 30%	Rural roads	Road cleaning	1.00E-02	1.30E-02
6	**Tyre wear**	Transfer coefficients	Increase with 30%	Rural roads	Road cleaning	2.00E-02	2.60E-02
6	**Tyre wear**	Transfer coefficients	Decrease	Rural roads	Road side soil (micro)	9.00E-01	8.91E-01
6	**Tyre wear**	Transfer coefficients	No change	Rural roads	Surface water (micro)	1.00E-01	1.00E-01
6	**Tyre wear**	Transfer coefficients	No change	Urban roads	Outdoor air (micro)	5.00E-02	5.00E-02
6	**Tyre wear**	Transfer coefficients	No change	Urban roads	Outdoor air (micro)	1.00E-01	1.00E-01
6	**Tyre wear**	Transfer coefficients	Increase with 30%	Urban roads	Road cleaning	1.00E-01	1.30E-01
6	**Tyre wear**	Transfer coefficients	Increase with 30%	Urban roads	Road cleaning	2.00E-02	2.60E-02
6	**Tyre wear**	Transfer coefficients	No change	Urban roads	Road runoff	rest	rest
6	**Tyre wear**	Transfer coefficients	No change	Urban roads	Road side soil (micro)	4.00E-01	4.00E-01

Measure ID	Source	Type of alteration	Change	From compartment	To compartment	Old value	New value
7	**Paint**	Input		Paint			
8	**Paint**	Lifetimes					
9	**Paint**	Transfer coefficients	Reduce only washing TC	Wall paint (DIY) indoor	Wall paint (DIY) indoor on brush	1.46E-03	1.02E-03
9	**Paint**	Transfer coefficients	The part not rinsed goes to mixed waste	Wall paint (DIY) indoor	Mixed waste collection (micro)	0.00E+00	4.37E-04
10	**Paint**	Transfer coefficients	Decrease 30%	Ship paint (prof) (discarded)	Surface water (micro)	1.00E-02	7.00E-03
10	**Paint**	Transfer coefficients	Decrease 30%	Ship paint (recr) (discarded)	Surface water (micro)	5.00E-02	3.50E-02
10	**Paint**	Transfer coefficients	Decrease 30%	Lacquer (prof) outdoor (discarded)	Outdoor air (micro)	1.60E-03	1.12E-03
10	**Paint**	Transfer coefficients	Decrease 30%	Lacquer (prof) outdoor (discarded)	Wastewater (micro)	1.26E-02	8.82E-03
10	**Paint**	Transfer coefficients	Decrease 30%	Lacquer (prof) outdoor (discarded)	Residential soil (micro)	1.67E-02	1.17E-02
10	**Paint**	Transfer coefficients	Decrease 30%	Lacquer (prof) outdoor (discarded)	Surface water (micro)	1.10E-03	7.70E-04
10	**Paint**	Transfer coefficients	Decrease 30%	Lacquer (prof) indoor (discarded)	Indoor air (micro)	3.20E-02	2.24E-02
10	**Paint**	Transfer coefficients	Decrease 30%	Wood stain (prof) outdoor (discarded)	Outdoor air (micro)	1.60E-03	1.12E-03
10	**Paint**	Transfer coefficients	Decrease 30%	Wood stain (prof) outdoor (discarded)	Wastewater (micro)	1.26E-02	8.82E-03
10	**Paint**	Transfer coefficients	Decrease 30%	Wood stain (prof) outdoor (discarded)	Residential soil (micro)	1.67E-02	1.17E-02

Measure ID	Source	Type of alteration	Change	From compartment	To compartment	Old value	New value
10	**Paint**	Transfer coefficients	Decrease 30%	Wood stain (prof) outdoor (discarded)	Surface water (micro)	1.10E-03	7.70E-04
10	**Paint**	Transfer coefficients	Decrease 30%	Wood stain (prof) indoor (discarded)	Indoor air (micro)	3.20E-02	2.24E-02
10	**Paint**	Transfer coefficients	Decrease 30%	Paints used in pre-made wooden products outdoor (discarded)	Outdoor air (micro)	1.60E-03	1.12E-03
10	**Paint**	Transfer coefficients	Decrease 30%	Paints used in pre-made wooden products outdoor (discarded)	Wastewater (micro)	1.26E-02	8.82E-03
10	**Paint**	Transfer coefficients	Decrease 30%	Paints used in pre-made wooden products outdoor (discarded)	Residential soil (micro)	1.67E-02	1.17E-02
10	**Paint**	Transfer coefficients	Decrease 30%	Paints used in pre-made wooden products outdoor (discarded)	Surface water (micro)	1.10E-03	7.70E-04
10	**Paint**	Transfer coefficients	Decrease 30%	Paints used in pre-made wooden products indoor (discarded)	Indoor air (micro)	3.20E-02	2.24E-02
10	**Paint**	Transfer coefficients	Decrease 30%	Lacquer (DIY) outdoor (discarded)	Outdoor air (micro)	1.60E-03	1.12E-03
10	**Paint**	Transfer coefficients	Decrease 30%	Lacquer (DIY) outdoor (discarded)	Wastewater (micro)	1.26E-02	8.82E-03
10	**Paint**	Transfer coefficients	Decrease 30%	Lacquer (DIY) outdoor (discarded)	Residential soil (micro)	1.67E-02	1.17E-02
10	**Paint**	Transfer coefficients	Decrease 30%	Lacquer (DIY) outdoor (discarded)	Surface water (micro)	1.10E-03	7.70E-04
10	**Paint**	Transfer coefficients	Decrease 30%	Lacquer (DIY) indoor (discarded)	Indoor air (micro)	6.40E-02	4.48E-02
10	**Paint**	Transfer coefficients	Decrease 30%	Other paint uses (DIY) outdoor (discarded)	Outdoor air (micro)	3.20E-03	2.24E-03

Measure ID	Source	Type of alteration	Change	From compartment	To compartment	Old value	New value
10	**Paint**	Transfer coefficients	Decrease 30%	Other paint uses (DIY) outdoor (discarded)	Wastewater (micro)	2.52E-02	1.77E-02
10	**Paint**	Transfer coefficients	Decrease 30%	Other paint uses (DIY) outdoor (discarded)	Residential soil (micro)	3.34E-02	2.34E-02
10	**Paint**	Transfer coefficients	Decrease 30%	Other paint uses (DIY) outdoor (discarded)	Surface water (micro)	2.18E-03	1.52E-03
10	**Paint**	Transfer coefficients	Decrease 30%	Other paint uses (DIY) indoor (discarded)	Indoor air (micro)	6.40E-02	4.48E-02
11	**Clothing and home textiles**	Input		Clothing (product sector)			
12	**Clothing and home textiles**	Lifetimes					
13	**Clothing and home textiles**	Transfer coefficients	Reduce TC	Disposable cleaning cloths	Wastewater (micro)	1.76E-02	1.23E-02
13	**Clothing and home textiles**	Transfer coefficients	No change	Textile coating (in use)	Wastewater (micro)	rest	rest
13	**Clothing and home textiles**	Transfer coefficients					
13	**Clothing and home textiles**	Transfer coefficients	Make 1-rest*0.7 and make a new link to mixed waste collection with rest!	Clothing (in use)	Clothing (in use) wash & dry	rest	8.77E-01
13	**Clothing and home textiles**	Transfer coefficients	Make 1-rest*0.7 and make a new link to mixed	Clothing (in use)	Mixed waste collection (micro)	0.00E+00	rest

Measure ID	Source	Type of alteration	Change	From compartment	To compartment	Old value	New value
			waste collection with rest!				
13	**Clothing and home textiles**	Transfer coefficients	No change	Clothing (in use)	Clothing (in use) wear & tear	2.26E-02	2.26E-02
13	**Clothing and home textiles**	Transfer coefficients	No change	Clothing (in use)	Clothing (in use) wear & tear	3.29E-01	3.29E-01
13	**Clothing and home textiles**	Transfer coefficients	No change	Home textiles (in use)	Indoor air (micro)	3.29E-01	3.29E-01
13	**Clothing and home textiles**	Transfer coefficients	No change	Home textiles (in use)	Indoor air (micro)	4.25E-01	4.25E-01
13	**Clothing and home textiles**	Transfer coefficients	Make 1-rest*0.7 and make a new link to mixed waste collection with rest!	Home textiles (in use)	Wastewater (micro)	rest	4.36E-01
13	**Clothing and home textiles**	Transfer coefficients	Make 1-rest*0.7 and make a new link to mixed waste collection with rest!	Home textiles (in use)	Mixed waste collection (micro)	0.00E+00	rest
14	**Technical textiles**	Input	Change 'Input projections' to 'Input projections new'	Technical textiles			
15	**Technical textiles**	Transfer coefficients	Decrease 30%	Technical home textiles (discarded)	Dumping	2.70E-04	1.89E-04

Measure ID	Source	Type of alteration	Change	From compartment	To compartment	Old value	New value
15	**Technical textiles**	Transfer coefficients	Decrease 30%	Other technical textiles	Dumping	2.70E-04	1.89E-04
15	**Technical textiles**	Transfer coefficients	Decrease 30%	Agrotextiles (discarded)	Dumping	2.70E-04	1.89E-04
15	**Technical textiles**	Transfer coefficients	Decrease 30%	Building textiles (discarded)	Dumping	2.70E-04	1.89E-04
15	**Technical textiles**	Transfer coefficients	Decrease 30%	Geotextiles (discarded)	Dumping	2.70E-04	1.89E-04
15	**Technical textiles**	Transfer coefficients					
15	**Technical textiles**	Transfer coefficients	Increase 30%	Textile waste collection	Textile recycling	1.44E-02	1.87E-02
15	**Technical textiles**	Transfer coefficients	Increase 30%	Technical home textiles (discarded)	Textile waste collection	4.46E-01	5.80E-01
15	**Technical textiles**	Transfer coefficients					
15	**Technical textiles**	Transfer coefficients	Change 1 to 0.7 and 0.3 to recycling	Medical textiles	Mixed waste collection	1.00E+00	7.00E-01
15	**Technical textiles**	Transfer coefficients	Add this flow (compartments exist)	Medical textiles	Textile recycling	0.00E+00	3.00E-01
15	**Technical textiles**	Transfer coefficients					
15	**Technical textiles**	Transfer coefficients	Decrease 30%	ELV textiles collection	Incineration	1.00E+00	7.00E-01
15	**Technical textiles**	Transfer coefficients	Decrease 30%	ELV textiles collection	Incineration	5.00E-01	3.50E-01
15	**Technical textiles**	Transfer coefficients	Decrease 30%	ELV textiles collection	Incineration	1.00E+00	7.00E-01

Measure ID	Source	Type of alteration	Change	From compartment	To compartment	Old value	New value
15	**Technical textiles**	Transfer coefficients	No change	ELV textiles collection	Landfill	rest	rest
15	**Technical textiles**	Transfer coefficients	Add this flow, 30%	ELV textiles collection	Textile recycling	0.00E+00	3.00E-01
15	**Technical textiles**	Transfer coefficients					
15	**Technical textiles**	Transfer coefficients	No change	Other technical textiles	Mixed waste collection	rest	rest
15	**Technical textiles**	Transfer coefficients	Add this flow	Other technical textiles	Textile recycling	0.00E+00	3.00E-01
15	**Technical textiles**	Transfer coefficients					
15	**Technical textiles**	Transfer coefficients	Decrease 30%	Construction and demolition incinerable waste collection	Litter on road sides	1.30E-03	9.10E-04
15	**Technical textiles**	Transfer coefficients	Decrease 30%	Construction and demolition incinerable waste collection	Litter on road sides	1.47E-02	1.03E-02
15	**Technical textiles**	Transfer coefficients	Decrease 30%	Construction and demolition incinerable waste collection	Litter on road sides	1.30E-03	9.10E-04
15	**Technical textiles**	Transfer coefficients	Decrease 30%	Construction and demolition incinerable waste collection	Litter on road sides	1.47E-02	1.03E-02
15	**Technical textiles**	Transfer coefficients					
15	**Technical textiles**	Transfer coefficients	Increase by 30%	Agricultural waste collection	Agricultural plastic recycling	1.20E-01	1.56E-01
15	**Technical textiles**	Transfer coefficients	Increase by 30%	Agricultural waste collection	Agricultural plastic recycling	1.33E-01	1.73E-01
15	**Technical textiles**	Transfer coefficients	Increase by 30%	Agricultural waste collection	Agricultural plastic recycling	2.67E-01	3.47E-01
15	**Technical textiles**	Transfer coefficients	Increase by 30%	Agricultural waste collection	Agricultural plastic recycling	2.00E-01	2.60E-01

Measure ID	Source	Type of alteration	Change	From compartment	To compartment	Old value	New value
15	**Technical textiles**	Transfer coefficients	Decrease by 30%	Agricultural waste collection	Residential soil (macro)	1.00E-04	7.00E-05
16	**Technical textiles**	Transfer coefficients	Reduce by 30% the losses and add to mixed waste	Agrotextiles (in use)	Agricultural soil (macro)	8.67E-01	6.07E-01
16	**Technical textiles**	Transfer coefficients	No change	Agrotextiles (in use)	Agricultural soil (micro)	rest	
16	**Technical textiles**	Transfer coefficients	Add flow	Agrotextiles (in use)	Mixed waste collection		3.00E-01
16	**Technical textiles**	Transfer coefficients	Reduce by 30% the losses and add to mixed waste	Building textiles (in use)	Residential soil (macro)	1.00E+00	7.00E-01
16	**Technical textiles**	Transfer coefficients		Building textiles (in use)	Mixed waste collection		3.00E-01
16	**Technical textiles**	Transfer coefficients	Reduce by 30% the losses and add to mixed waste	Geotextiles (in use)	Residential soil (macro)	9.77E-02	6.84E-02
16	**Technical textiles**	Transfer coefficients	Reduce by 30% the losses and add to mixed waste	Geotextiles (in use)	Residential soil (macro)	5.51E-01	3.85E-01
16	**Technical textiles**	Transfer coefficients	No change	Geotextiles (in use)	Sub-surface soil (micro)	rest	
16	**Technical textiles**	Transfer coefficients	Add flow	Geotextiles (in use)	Mixed waste collection		3.00E-01
17	Agriculture	Transfer coefficients	Increase	Agricultural waste collection	Agricultural plastic recycling	1.20E-01	1.56E-01
17	Agriculture	Transfer coefficients	Increase	Agricultural waste collection	Agricultural plastic recycling	1.33E-01	1.73E-01
17	Agriculture	Transfer coefficients	Increase	Agricultural waste collection	Agricultural plastic recycling	2.67E-01	3.47E-01

Measure ID	Source	Type of alteration	Change	From compartment	To compartment	Old value	New value
17	Agriculture	Transfer coefficients	Increase	Agricultural waste collection	Agricultural plastic recycling	2.00E-01	2.60E-01
17	Agriculture	Transfer coefficients	no change	Agricultural waste collection	Incineration	rest	rest
17	Agriculture	Transfer coefficients	Increase	Agricultural waste collection (micro)	Agricultural plastic recycling	1.20E-01	1.56E-01
17	Agriculture	Transfer coefficients	Increase	Agricultural waste collection (micro)	Agricultural plastic recycling	1.33E-01	1.73E-01
17	Agriculture	Transfer coefficients	Increase	Agricultural waste collection (micro)	Agricultural plastic recycling	2.67E-01	3.47E-01
17	Agriculture	Transfer coefficients	Increase	Agricultural waste collection (micro)	Agricultural plastic recycling	2.00E-01	2.60E-01
17	Agriculture	Transfer coefficients	no change	Agricultural waste collection (micro)	Incineration	rest	rest
18	Agriculture	Input	Lower input with 30%	Agriculture			
19	Macroplastics	Input	Decrease input from 2025-2050 by 30%	Packaging, agriculture, clothing, textiles			
20	Macroplastics	Lifetimes	Increase lifetime vector by 30%				
21	Macroplastics	Transfer coefficients	Decrease TC by 30%	Packaging recycling	Industrial storm water (micro)	4.00E-09	2.80E-09
21	Macroplastics	Transfer coefficients	Decrease TC by 30%	Packaging recycling	Industrial storm water (micro)	1.60E-06	1.12E-06
21	Macroplastics	Transfer coefficients	Decrease TC by 30%	Packaging recycling	Residential soil (micro)	9.96E-07	6.97E-07
21	Macroplastics	Transfer coefficients	Decrease TC by 30%	Packaging recycling	Residential soil (micro)	3.98E-04	2.79E-04
21	Macroplastics	Transfer coefficients					

Measure ID	Source	Type of alteration	Change	From compartment	To compartment	Old value	New value
21	Macroplastics	Transfer coefficients	Decrease TC by 30%	Textile recycling	Wastewater (micro)	4.00E-09	2.80E-09
21	Macroplastics	Transfer coefficients	Decrease TC by 30%	Textile recycling	Wastewater (micro)	1.60E-06	1.12E-06
21	Macroplastics	Transfer coefficients	Decrease TC by 30%	Textile recycling	Residential soil (micro)	9.92E-07	6.94E-07
21	Macroplastics	Transfer coefficients	Decrease TC by 30%	Textile recycling	Residential soil (micro)	3.97E-04	2.78E-04
21	Macroplastics	Transfer coefficients	Decrease TC by 30%	Textile recycling	Outdoor air (micro)	4.00E-09	2.80E-09
21	Macroplastics	Transfer coefficients	Decrease TC by 30%	Textile recycling	Outdoor air (micro)	1.60E-06	1.12E-06
21	Macroplastics	Transfer coefficients					
21	Macroplastics	Transfer coefficients	Decrease TC by 30%	Agricultural plastic recycling	Residential soil (micro)	9.96E-07	6.97E-07
21	Macroplastics	Transfer coefficients	Decrease TC by 30%	Agricultural plastic recycling	Residential soil (micro)	3.98E-04	2.79E-04
21	Macroplastics	Transfer coefficients	Decrease TC by 30%	Agricultural plastic recycling	Industrial stormwater (micro)	4.00E-09	2.80E-09
21	Macroplastics	Transfer coefficients	Decrease TC by 30%	Agricultural plastic recycling	Industrial stormwater (micro)	1.60E-06	1.12E-06
22	Macroplastics	Transfer coefficients	All TCs leading to macroplastic sinks is reduced by 30%. Or TCs to waste collection are increased by 30%!				
22	Macroplastics	Transfer coefficients	Increase 30%	Litter in natural environments	Mixed waste collection	1.00E-01	1.30E-01
22	Macroplastics	Transfer coefficients	Increase 30%, to max of 1	Litter in natural environments	Mixed waste collection	9.00E-01	1.00E+00
22	Macroplastics	Transfer coefficients	REST	Litter in natural environments	Natural soil (macro)	rest	
22	Macroplastics	Transfer coefficients	Decrease 30%	Litter in natural environments	Surface water (macro)	1.02E-03	7.14E-04

Measure ID	Source	Type of alteration	Change	From compartment	To compartment	Old value	New value
22	Macroplastics	Transfer coefficients	REST	Litter in residential environments	Mixed waste collection	rest	
22	Macroplastics	Transfer coefficients	Decrease 30%	Litter in residential environments	Residential soil (macro)	1.17E-02	8.19E-03
22	Macroplastics	Transfer coefficients	Decrease 30%	Litter in residential environments	Stormwater (macro)	1.00E-02	7.00E-03
22	Macroplastics	Transfer coefficients	Decrease 30%	Litter in residential environments	Surface water (macro)	1.02E-03	7.14E-04
22	Macroplastics	Transfer coefficients	Increase 30%	Litter on road sides	Mixed waste collection	1.00E-01	1.30E-01
22	Macroplastics	Transfer coefficients	Increase 30%, to max of 1	Litter on road sides	Mixed waste collection	9.00E-01	1.00E+00
22	Macroplastics	Transfer coefficients	REST	Litter on road sides	Road side soil (macro)	rest	
22	Macroplastics	Transfer coefficients					
22	Macroplastics	Transfer coefficients	Decrease 30%	Collected organic waste (larger than 1 mm)	Compost size separation (fictional process)	1.00E-02	7.00E-03
22	Macroplastics	Transfer coefficients					
22	Macroplastics	Transfer coefficients	0	Agricultural packaging bottles	Agricultural soil (macro)	0.00E+00	
22	Macroplastics	Transfer coefficients	Decrease 30%	Agricultural packaging bottles	Agricultural soil (macro)	1.60E-02	1.12E-02
22	Macroplastics	Transfer coefficients	0	Agricultural packaging films	Agricultural soil (macro)	0.00E+00	
22	Macroplastics	Transfer coefficients	Decrease 30%	Agricultural packaging films	Agricultural soil (macro)	5.90E-02	4.13E-02
22	Macroplastics	Transfer coefficients	0	Agricultural mulching films	Agricultural soil (macro)	0.00E+00	

Measure ID	Source	Type of alteration	Change	From compartment	To compartment	Old value	New value
22	Macroplastics	Transfer coefficients	Decrease 30%	Agricultural mulching films	Agricultural soil (macro)	3.70E-02	2.59E-02
22	Macroplastics	Transfer coefficients	0	Agricultural other	Agricultural soil (macro)	0.00E+00	
22	Macroplastics	Transfer coefficients	Decrease 30%	Agricultural other	Agricultural soil (macro)	3.80E-02	2.66E-02
22	Macroplastics	Transfer coefficients	0	Agricultural greenhouse films (in use)	Agricultural soil (macro)	0.00E+00	
22	Macroplastics	Transfer coefficients	Decrease 30%	Agricultural greenhouse films (in use)	Agricultural soil (macro)	4.02E-01	2.82E-01
22	Macroplastics	Transfer coefficients	Decrease 30%	Agricultural waste collection	Residential soil (macro)	1.00E-04	7.00E-05
22	Macroplastics	Transfer coefficients	Decrease 30%	Packaging collection	Residential soil (macro)	1.00E-04	7.00E-05
22	Macroplastics	Transfer coefficients	Decrease 30%	Mixed waste collection	Residential soil (macro)	1.00E-04	7.00E-05
22	Macroplastics	Transfer coefficients	Decrease 30%	Geotextiles	Geotextiles (in use)	1.33E-02	9.31E-03
22	Macroplastics	Transfer coefficients	Decrease 30%	Geotextiles	Geotextiles (in use)	2.67E-02	1.87E-02
22	Macroplastics	Transfer coefficients	Decrease 30%	Agrotextiles	Agrotextiles (in use)	9.80E-02	6.86E-02
22	Macroplastics	Transfer coefficients	Decrease 30%	Textile waste collection	Residential soil (macro)	1.00E-04	7.00E-05
22	Macroplastics	Transfer coefficients	Decrease 30%	Building textiles	Building textiles (in use)	1.30E-03	9.10E-04
22	Macroplastics	Transfer coefficients	Decrease 30%	Building textiles	Building textiles (in use)	1.47E-02	1.03E-02
22	Macroplastics	Transfer coefficients	Make 0.3 as minimum	Combined sewer overflow (macro)	Incineration	0.00E+00	3.00E-01
22	Macroplastics	Transfer coefficients	1	Combined sewer overflow (macro)	Incineration	1.00E+00	

Measure ID	Source	Type of alteration	Change	From compartment	To compartment	Old value	New value
23	Intentionally produced microparticles	Input					

11 Appendix D – Additional supporting figures

11.1 Additional figures NL

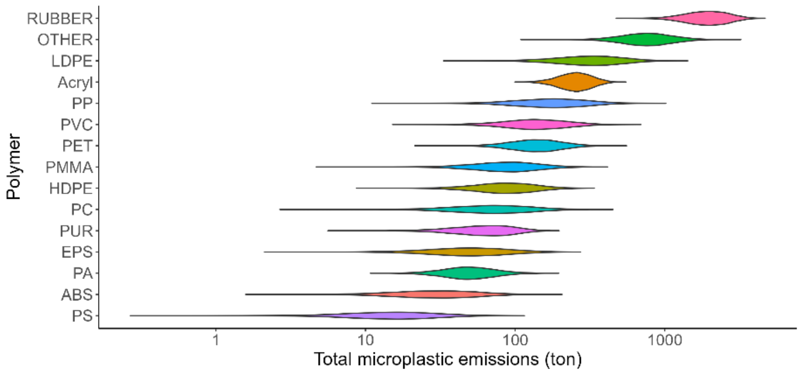

Figure D1 Distribution of polymer types emitted to water as microplastics.

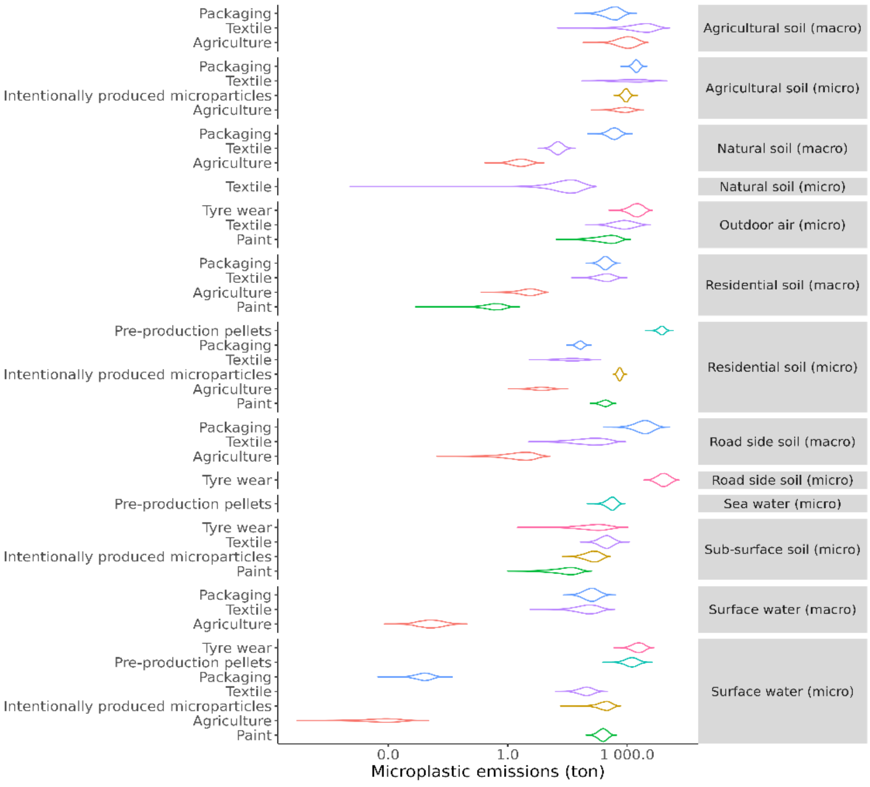

Figure D2 Microplastic emissions from each source to sinks.

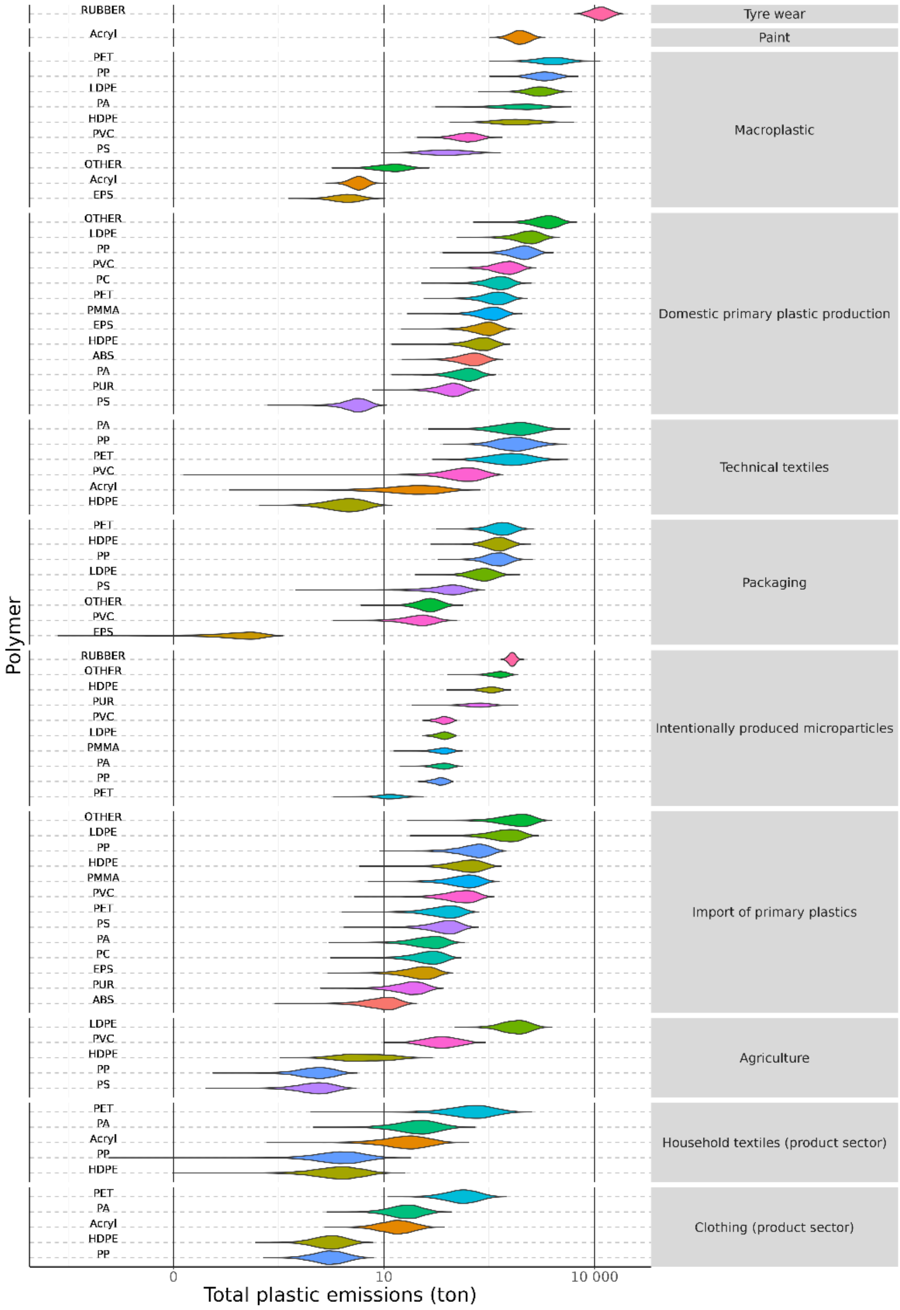

Figure D3 Polymer distribution for each source.

11.2 Additional figures EU

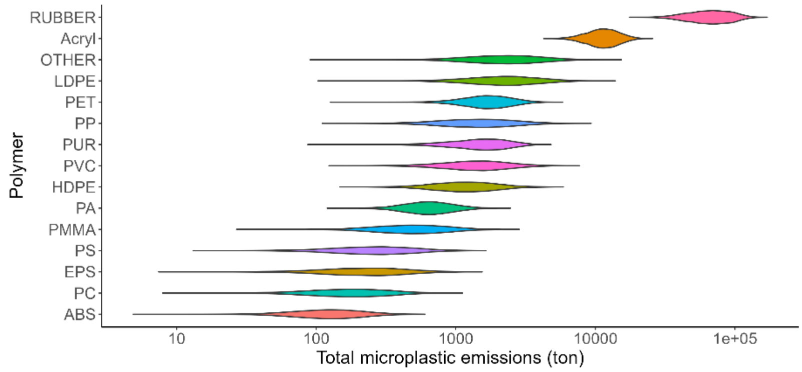

Figure D4 Distribution of polymer types emitted to water as microplastics.

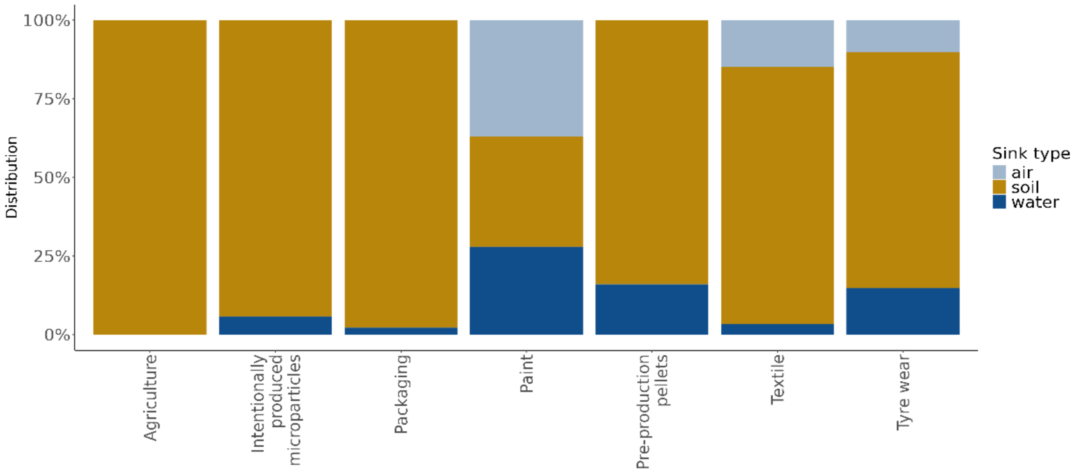

Figure D5 Emissions to water, soil and air.

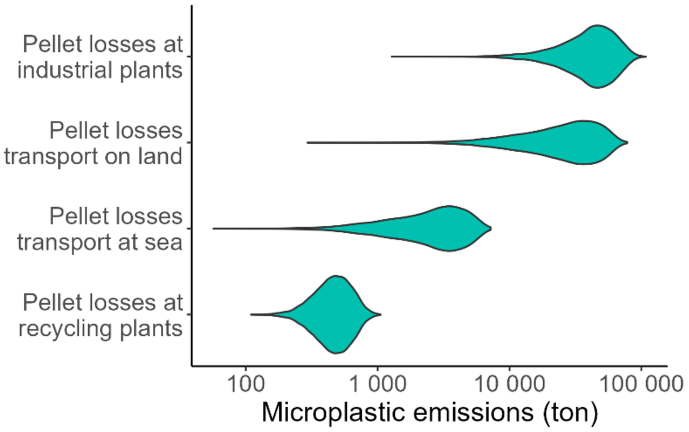

Figure D6 Various sources of pre-production pellet losses contributing towards the total emission to the environment.

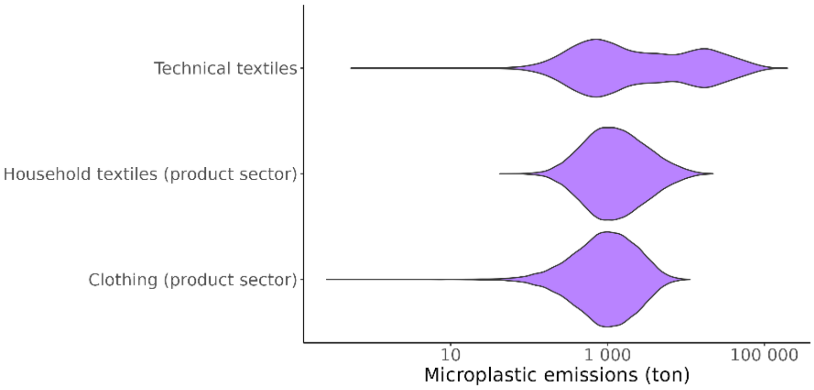

Figure D7 Emission of textile microplastics to the environment coming from technical, household and clothing textiles.

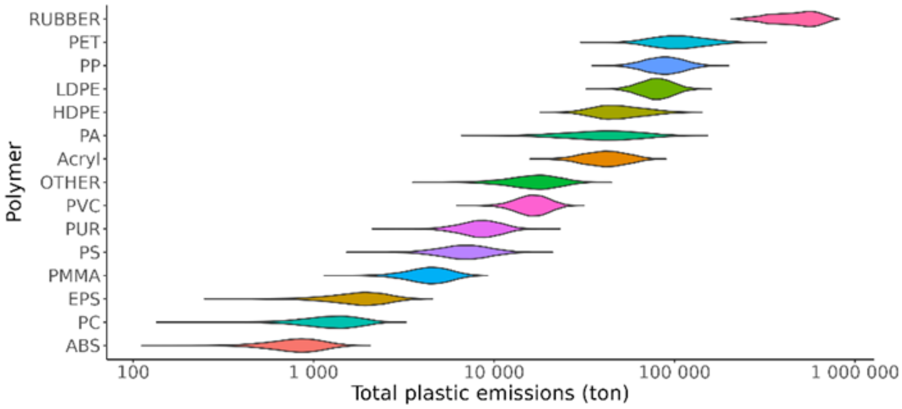

Figure D8 Distribution of polymer types emitted as microplastics to the environment.

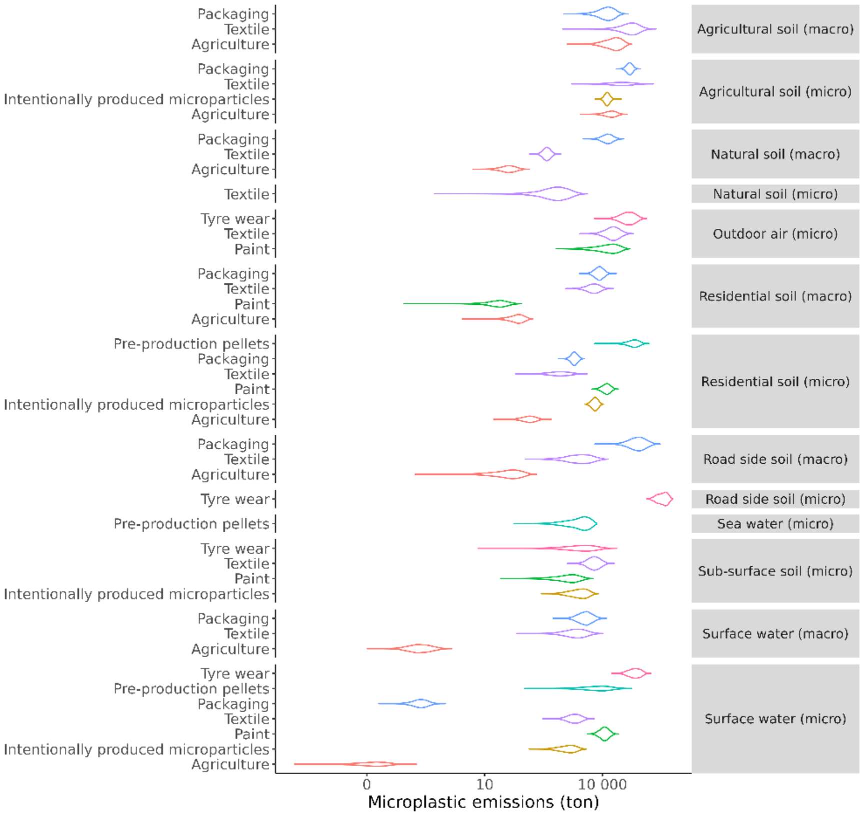

Figure D9 Microplastic emissions from each source to sinks.

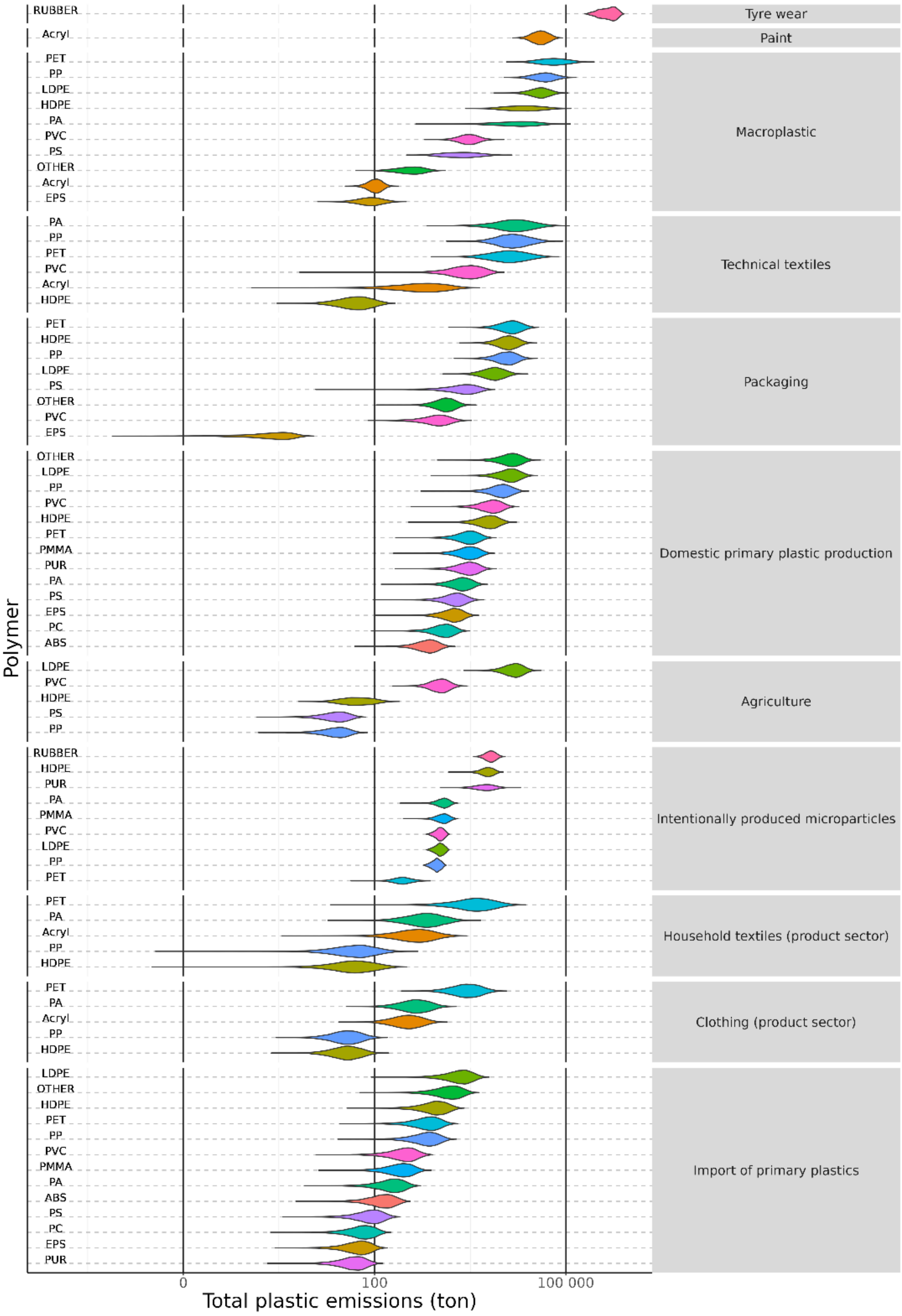

Figure D10 Polymer distribution for each source.

11.3 Global Sensitivity Analysis

Figure D11 Sobol Indices for Import of pre-production pellets from global sensitivity analysis of input variation in transfer coefficients in relation to output variation of plastics emitted to the environment.

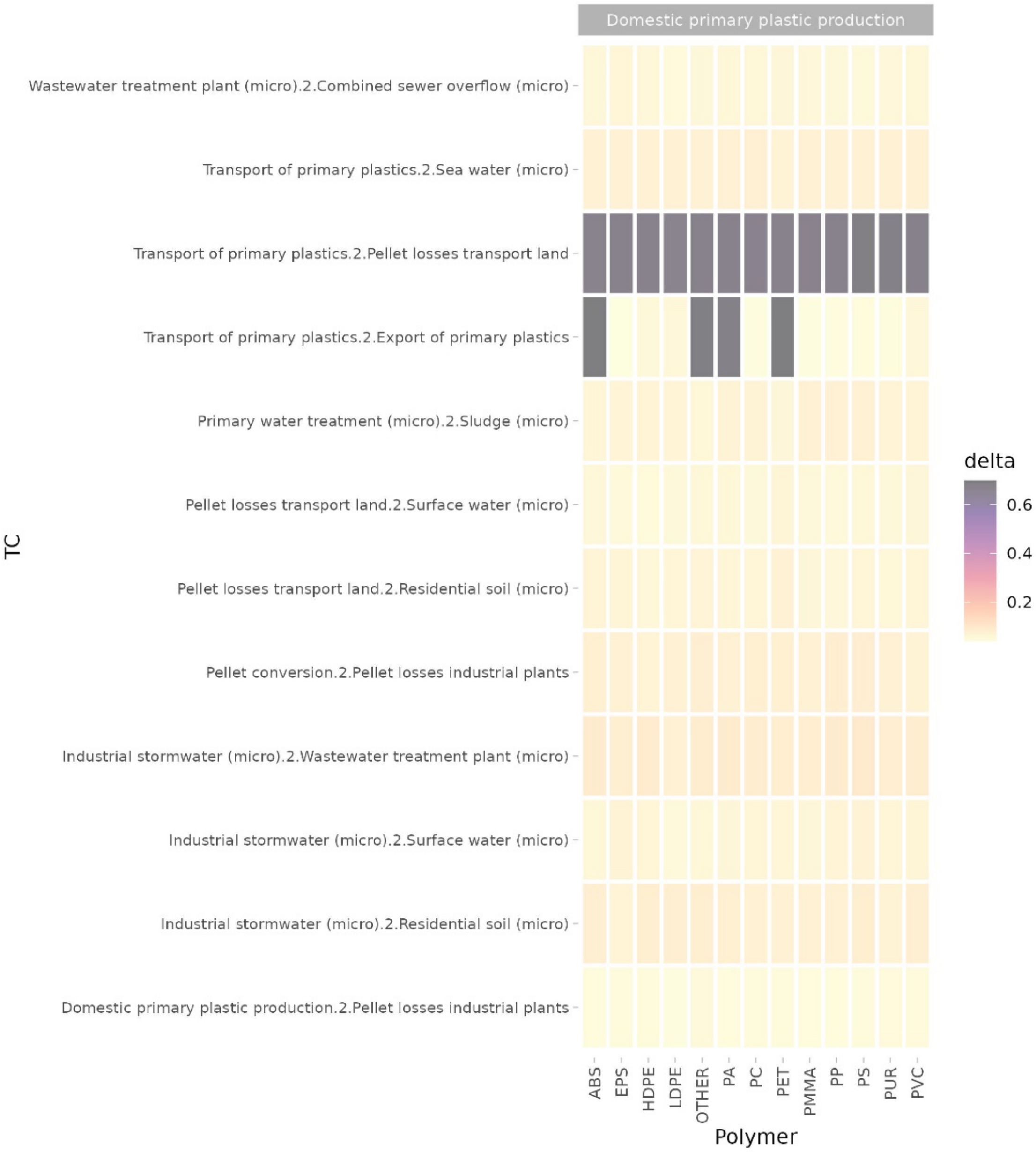

Figure D12 Sobol Indices for Domestic production of pre-production pellets from global sensitivity analysis of input variation in transfer coefficients in relation to output variation of plastics emitted to the environment.

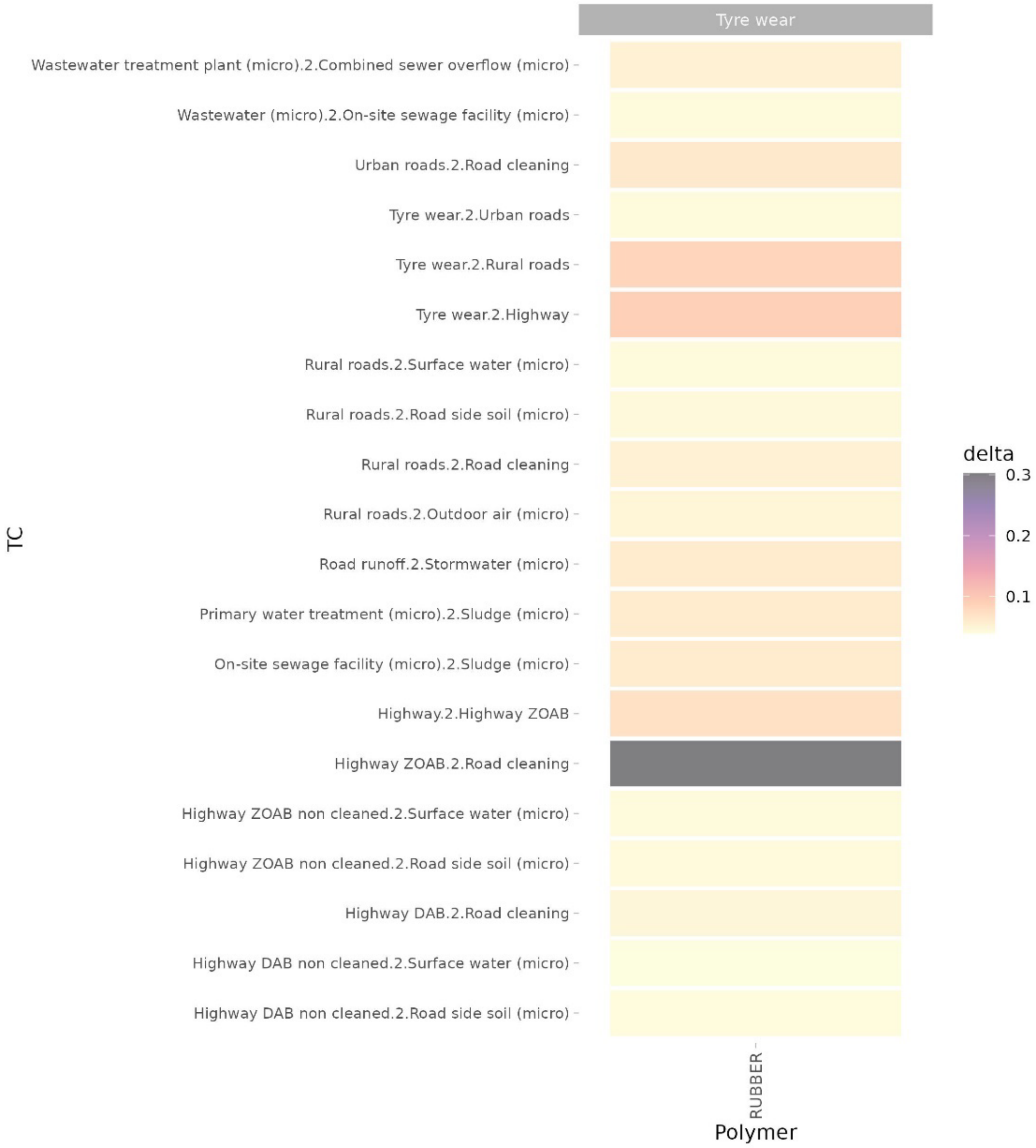

Figure D13 Sobol Indices for Tyre wear from global sensitivity analysis of input variation in transfer coefficients in relation to output variation of plastics emitted to the environment.

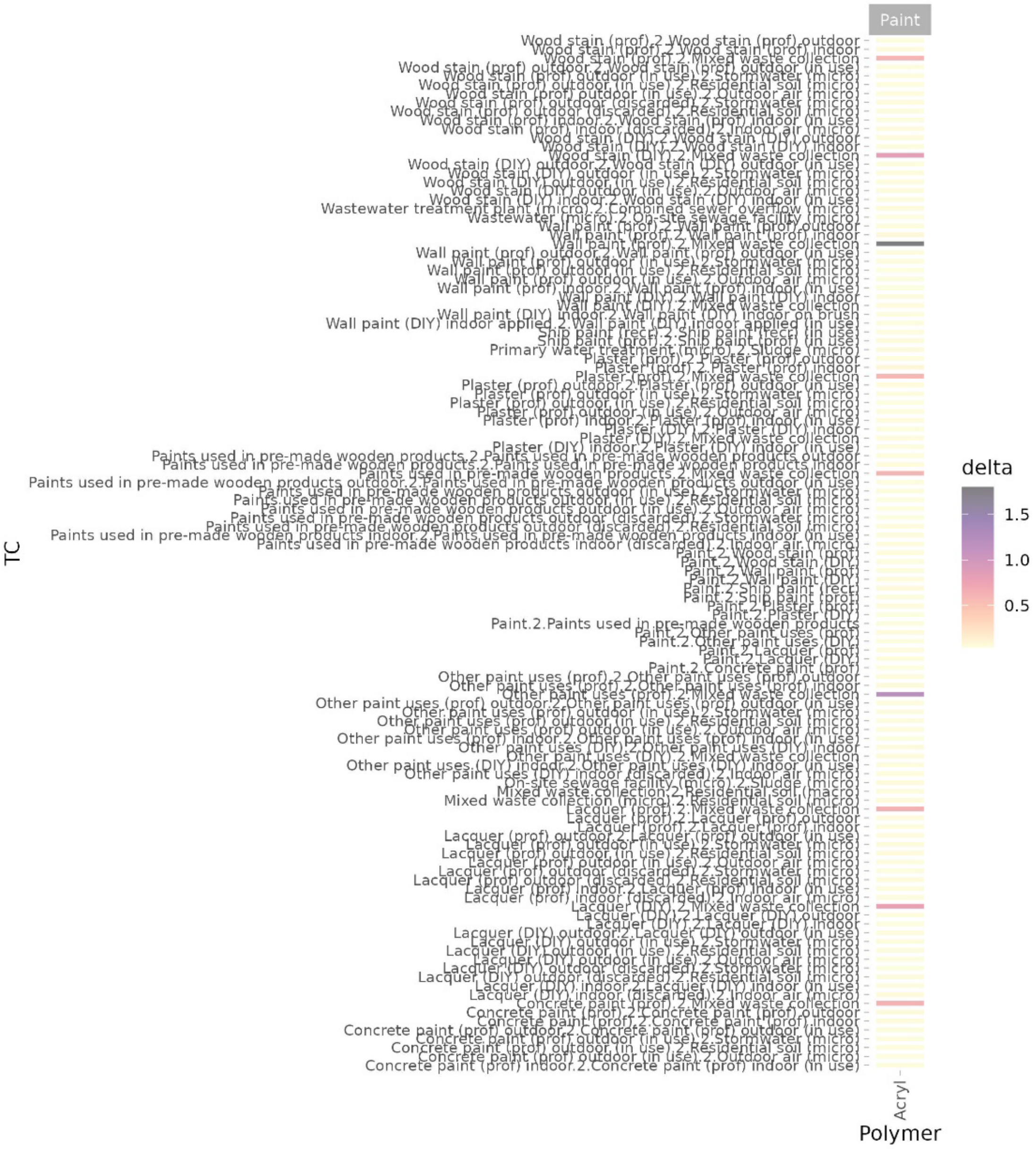

Figure D14 Sobol Indices for Paint from global sensitivity analysis of input variation in transfer coefficients in relation to output variation of plastics emitted to the environment.

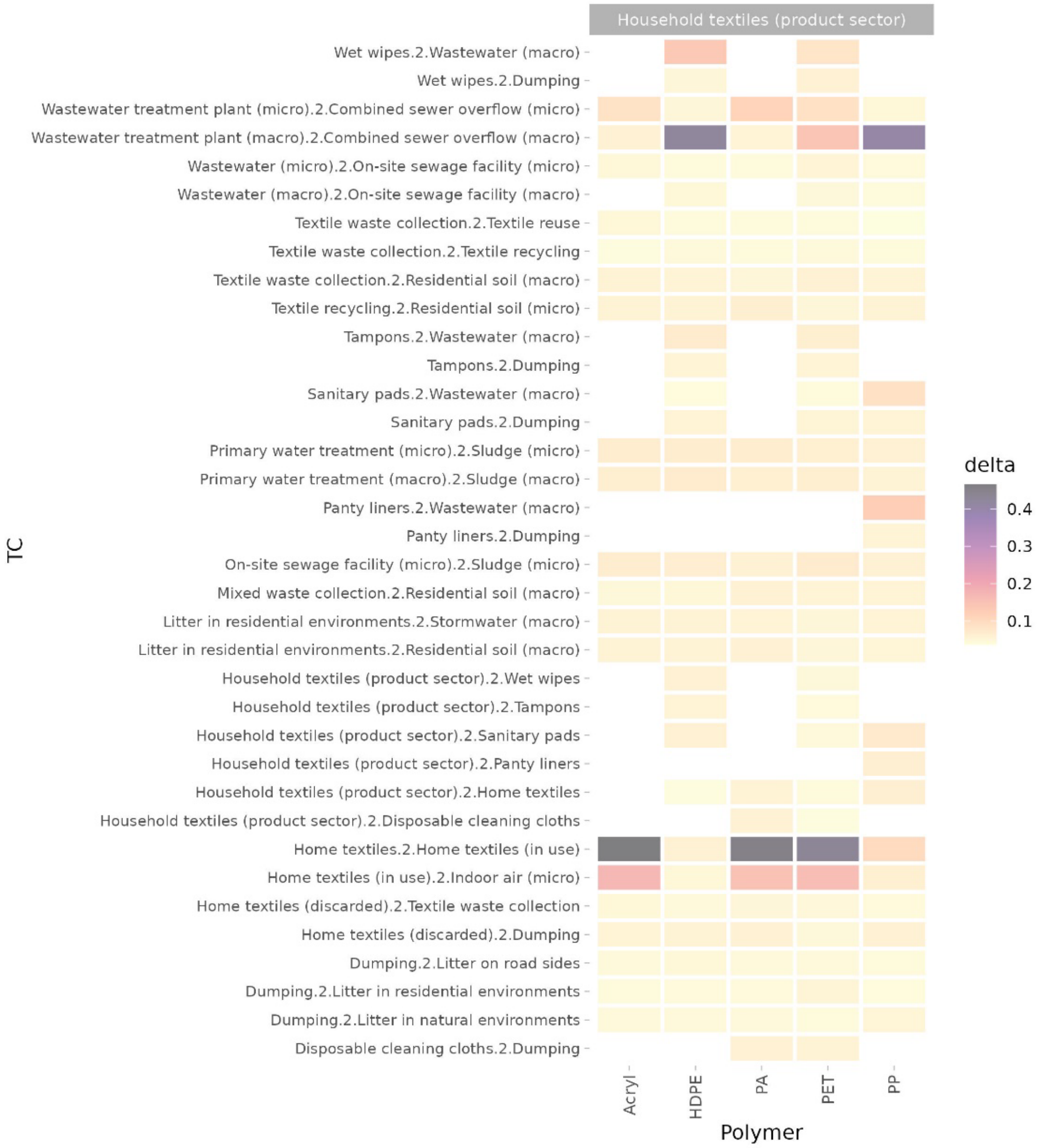

Figure D15 Sobol Indices for Household textiles from global sensitivity analysis of input variation in transfer coefficients in relation to output variation of plastics emitted to the environment.

Figure D16 Sobol Indices for Technical textiles from global sensitivity analysis of input variation in transfer coefficients in relation to output variation of plastics emitted to the environment.

Figure D17 Sobol Indices for Clothing textiles from global sensitivity analysis of input variation in transfer coefficients in relation to output variation of plastics emitted to the environment.

Figure D18 Sobol Indices for Packaging from global sensitivity analysis of input variation in transfer coefficients in relation to output variation of plastics emitted to the environment.

Figure D19 Sobol Indices for Agriculture from global sensitivity analysis of input variation in transfer coefficients in relation to output variation of plastics emitted to the environment.

Published by:

National Institute for Public Health
and the Enviroment, RIVM
P.O. Box 1 | 3720 BA Bilthoven
The Netherlands
www.rivm.nl/en

August 2024

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