



Sources, transport, and accumulation of different types of plastic litter in aquatic environments: A review study[☆]

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ABSTRACT

Types of plastic waste in different aquatic environments were assessed to obtain a global framework of plastic waste transport and accumulation, relevant for plastic pollution mitigation strategies in aquatic environments. Packaging and consumer products were the most encountered product categories in rivers, while fishery items dominated in the oceanic environment. Plastics from electronics, building and construction, and transport were barely observed. For polymers, polyethylene and polypropylene contributed most to pollution in all environments. The highest diversity in polymer composition was found in oceanic and freshwater sediments. It is therefore argued that a large fraction of plastic waste accumulates here. This confirms that plastic waste transport and accumulation patterns were most affected by the density, surface area, and size of plastics. Only thick-walled, larger plastic debris from low-density polymers are transported through currents from rivers to ocean, while the larger fraction of plastic litter is likely retained in sediments or beaches.

1. Introduction

Because of the persistent qualities and high pollution rates of plastics to the environment, plastic pollution has been named as “one of the biggest environmental challenges of this lifetime” (UN environment, 2018). Presently, most attention targets plastic waste in the oceanic environments. The first observation of buoyant plastics in the oceans dates back to 1972 (Carpenter and Smith, 1972). Since then, numerous studies have been conducted on this topic to increase the understanding of oceanic plastic transport and accumulation zones (Goldstein et al., 2012; Law et al., 2010; Lebreton et al., 2012; Maximenko et al., 2012; Moore et al., 2001) and beach pollution (Derraik, 2002). More recently, studies also focus on riverine plastic pollution (Lechner et al., 2014), transport of plastics (Ryan, 2015; Siegfried et al., 2017), and the environmental impact of plastic on aquatic species (Gall and Thompson, 2015; Rochman et al., 2013). Most recent studies focus on obtaining a global plastic budget that links plastic to sources such as product category or polymer (Geyer et al., 2017; Ryberg et al., 2018).

To quantify environmental impact, Life Cycle Assessment (LCA) is a frequently used tool, especially for businesses and product designers. With an LCA, the environmental impacts of the product throughout all life stages of a product or technology are assessed. However, the impact of environmental plastic pollution is yet unaccounted for in these

methods. This blind spot in LCA results in an underestimation of the environmental impact of plastic materials. To include the aspect of plastic pollution consequences in LCA, data on plastic concentrations, fate, exposure, and effect levels have to be obtained. To assess plastic concentrations, an environmental framework is required that quantifies not only plastic losses to the environment but also their transport, accumulation areas, and the fluxes between them (Hoellein et al., 2014). However, there are still many steps to be studied before such a framework is completed. Modeling studies have estimated plastic waste quantities in rivers and oceans, and quantified the amount of plastic entering oceans from land-based sources (Jambeck et al., 2015; Lebreton et al., 2017; Schmidt et al., 2017; van Sebille et al., 2015). However, the quantities of buoyant plastic in oceanic environments are much lower than the estimates of plastic waste entering from land, meaning that there is a missing fraction in the environmental plastic budget. It is reported that only 1% of plastic waste is actually afloat in oceanic accumulation zones and that the fate of 99% of plastic waste remains unknown (ter Halle et al., 2016; van Sebille et al., 2015). Hence, the whereabouts of this missing fraction of plastic waste remains unknown. For example, the plastic waste might be accumulating in ocean or riverine sediments, on shorelines, or suspended in the “marine snow” of oceans (Taylor et al., 2016). Furthermore, estimates of emission quantities of plastic waste into the environment are available,

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Table 1

Studies that were used as input data for the polymer composition study. Furthermore, the locations of sampling, the allocated environment, and compartment were collected from the studies. The last column includes information on the plastic size class and details of type.

Source	Location	Environment	Compartment	Size (macro > 0.5, micro < 0.5 cm)
(Cooper and Corcoran, 2010)	Kauai, Hawaii Beach	Ocean	Beach	Plastic
(Corcoran et al., 2009)	Kauai, Hawaii Beach	Ocean	Beach	Microplastic
(Corcoran et al., 2015)	Lake Ontario sediment	Freshwater	Sediment	Microplastic
(Frias et al., 2010)	Portugal beach	Ocean	Beach	Microplastic
(Gasperi et al., 2014)	Seine River surface	Freshwater	Epipelagic	Macroplastic
(Imhof et al., 2013)	Italy Lake Garda	Freshwater	Beach	Microplastic
(Klein et al., 2015)	Rhine River	Freshwater	Sediment	Microplastic
(Lebreton et al., 2018)	Ocean, North Pacific subtropical gyre	Ocean	Epipelagic	Macro- and microplastic, lines and hard plastics
(Mani et al., 2015)	Rhine surface water	Freshwater	Epipelagic	Microplastic
(Martin et al., 2017)	Deep-sea Ireland	Ocean	Sediment	Microplastics, fibers, and fragments
(Ng and Obbard, 2006)	Singapore Seabed	Ocean	Sediment	Microplastic
(Ng and Obbard, 2006)	Singapore Seawater	Ocean	Epipelagic	Microplastic
(Pedrotti et al., 2016)	Mediterranean sea (coastal)	Ocean	Epipelagic	Micro- and macroplastic
(Peng et al., 2018)	Mariana trench	Ocean	Sediment	Microplastic
(Reisser et al., 2013)	Australia, coastal waters	Ocean	Epipelagic	Micro- and macroplastic, lines and hard plastics
(Sadri and Thompson, 2014)	Tamar estuary	Freshwater	Epipelagic	Micro- and macroplastic
(Su et al., 2016)	China lake Taihu	Freshwater	Sediment	Microplastic
(Vianello et al., 2013)	Venice Beach	Ocean	Sediment	Microplastic
(Yu et al., 2016)	China beach	Ocean	Beach	Microplastic
(Zbyszewski and Corcoran, 2011)	Lake Canada beach	Freshwater	Beach	Macro- and microplastic, lines and hard plastics
(Zhang et al., 2015)	China, Three Gorges Reservoir	Freshwater	Epipelagic	Microplastic
(Zhang et al., 2016)	Tibet river system	Freshwater	Beach	Microplastic
(Zhao and Zhu, 2011)	South China Sea	Ocean	Beach	Micro- and macroplastic

which include litter, mismanaged waste, sewage, and other sources (Hoorweg and Bhada-Tata, 2012; Jambeck et al., 2015). However, this data does not include specifications such as product type or plastic polymer type, which will likely affect the transport of the litter and therefore where it accumulates. Particularly transport of macroplastic waste (> 0.5 cm) is little studied. Although transport models have been further developed, for microplastic waste (> 0.5 cm), data input and validation by measurements are still required (Besseling et al., 2017; Kooi et al., 2018).

In this study, data on the composition of plastic waste in different aquatic environments are collected and compared. The composition of plastic waste is assessed on both plastic product category and plastic polymer type. The similarities and differences are used to identify the most likely accumulation zones, with support of existing theories and knowledge of the transport of plastics in the environment. Through this, individual studies on different aquatic sub-environments and regions are compared and linked to create a unique perspective and global overview on plastic waste transport and their accumulation areas. To achieve this, peer-reviewed studies on plastic pollution throughout different aquatic sub-environments are compiled in a literature review. Soil and terrestrial environments are excluded in this study, as comparisons between terrestrial and aquatic plastic litter requires a separate study. Furthermore, the composition of plastic pollution in environments is compared to production and waste data available to identify similarities and differences (Geyer et al., 2017). With this study, nuance can be given to models predicting plastic waste quantities in environments, which is required when concentrations of plastic waste in the environment have to be measured, such as in LCA.

2. Material and methods

Six different aquatic sub-environments, hereafter called “compartments”, were identified before the literature search. These compartments are beach, epipelagic, and sediment, for both freshwater and ocean. Beach studies included all studies on plastic polymers collected from oceanic and freshwater beaches, which cover the shoreline and banks. Epipelagic studies included all studies on plastics in the upper layer of the water column. Sediment studies involved all studies on plastics in the sediment layers in the benthic zone.

Plastic pollution studies were obtained through a thorough

literature collection, with searches including “plastic,” “ocean,” “river,” “sediment,” “beach,” “shore” in different arrangements. References within studies were also searched (Hidalgo-Ruz et al., 2012). Included were studies that reported counts on macro- and/or microplastics and that used Fourier-Transform Infrared spectroscopy (FT-IR) or other advanced polymer identification methods. Data reported on different locations or size classes were aggregated to form one group. Data from studies were included when there was quantity or percentile data available in graphs or tables on either polymer type or product category. All polymers reported in studies were included. However, to keep a focus on plastics, measurements of non-oil-based materials such as rayon or cellulose were excluded from the analysis. Polymers from these studies that were classified as “other” and “unknown” were combined in one class, “others”. If the contribution of this group was larger than 20%, the study was excluded from the analysis, as uncertainty would increase. Studies that sampled only microfibers were excluded from the analysis. A Kruskal-Wallis rank sum test was used to determine whether there was a significant difference in composition within and between the six environmental compartments.

When studies included data of plastic litter based on item per count, the items were categorized in the categories used in Geyer et al. (2017): “packaging,” “consumer,” “building and construction,” “electronic,” “textile,” “industrial,” and “other”. A category of “unknown” was included to summarize all unidentified plastic items. Items such as bottles, containers, and wrappers were identified as packaging. Consumer goods were all items that could be related to consumption that was not packaging, such as leisure, toiletries, or kitchen items. Construction items included all structural items, while transport included all motor, bicycle, car, or airplane fragments. Electronic items were items such as housing of game consoles or headphones. Industrial items are all large-scale items such as machine parts. Fishery industry items were identified as a separate group. Studies that mentioned only plastic shape such as “fiber,” “fragment,” “pellet,” or “film” were excluded from the analysis.

3. Results

3.1. Polymer categories

In total, twenty-three studies were compared for polymer

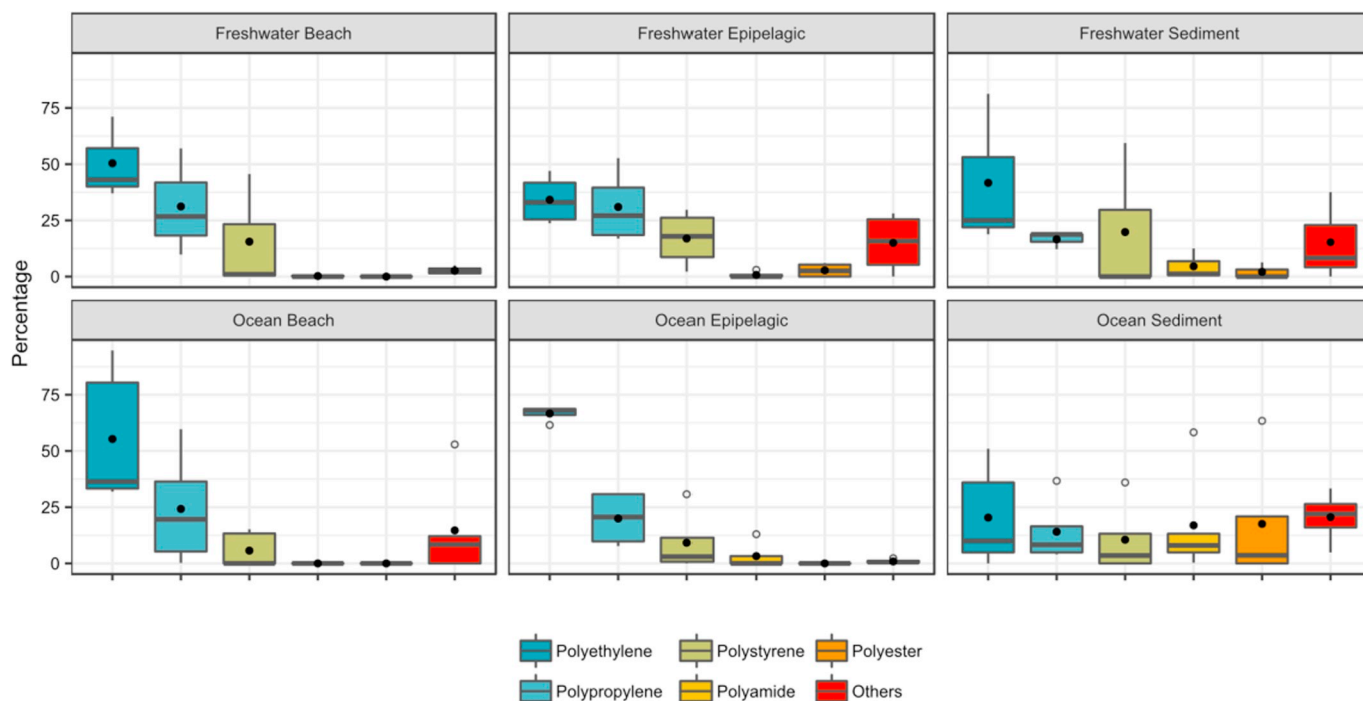


Fig. 1. Compositional data of six different polymer groups in the six environmental compartments distinguished in this paper. Upper and lower hinges represent the first and the third quantile, and whiskers represent a maximum of $1.5 \times$ the distance between the first and the third quantile. The black dots represent the mean value, the line in the box represents the median value, and the white dots represent the outliers.

composition on the basis of count (Table 1). Three studies covered *freshwater, sediment* and *freshwater, beach*. Four studies covered *freshwater, epipelagic*; *ocean, epipelagic*; and *ocean, sediment*. Five studies covered *ocean beach*. Fifteen of these studies focused on microplastics, one on macroplastics, six on both micro- and macroplastics, and one study did not specify. Areas that are relatively well studied are Europe, Mediterranean, and China, while areas lacking studies are Africa and South America.

Polyethylene (PE) was proportionally dominant in all environmental compartments, followed by polypropylene (PP) and polystyrene (PS) (Fig. 1). The polymer composition in *freshwater, beach*, and *ocean, epipelagic*, were most homogeneous, and PE, PP, and PS together represented on average 92.2% and 95.8% of encountered polymers, respectively. Least observed were polyester, polyamide (PA), and “others” (which included PET, PVC, PMMA, EVA, PAN, PVOH, and alkyd polymers; see Table 2 for explanations for the abbreviations). In the other four compartments, the contribution of “others” was larger. The contribution of “others” to the composition in *ocean, beach* was high as a result from a high (p)EVA contribution observed by Yu et al. (2016) along the Bohai Sea. For *freshwater, epipelagic*; *ocean, sediment*; and *freshwater, sediment*, “others” was relatively high due to high PET contributions. The polymer composition in *freshwater, sediment*, and *ocean, sediment* was most diverse. Here, polyester, PA, and PAN (in others) were often encountered; often these polymers are associated with fiber-based products. PA and polyester were especially high in *ocean, sediments*, with an average of 16.9% and 17.6%, respectively. In non-sediment compartments, PA and polyester contribution together contributed to a maximum of 3.5%. The contribution of PS polymers was highest in *freshwater, sediment*. Overall, PS was more represented in freshwater systems than in ocean; however, the spread in data was high.

The collected data contained a high variation for all polymers within all compartments (Fig. 1). The polymers within the groups *ocean, beach*; *ocean, epipelagic*; *freshwater, beach*; and *freshwater, epipelagic* varied significantly (Kruskal-Wallis rank-sum test: $P = 0.0004$, $P = 0.0008$, $P = 0.03$ and $P = 0.005$, respectively). Variation among

Table 2

The density of the most commonly produced polymers. For most polymers, a range is given, as density is product dependent. The density class was established based on average water density, where low density polymers are $< 1 \text{ g/cm}^3$, intermediate density polymers are between 1 and 1.1 g/cm^3 , and high-density polymers are $> 1.1 \text{ g/cm}^3$. Data is collected from Hidalgo-Ruz et al. (2012). Additional polymer data not included were collected online from Omnexus.

Polymer	Abbreviation	Min (g/ cm ³)	Max (g/ cm ³)	Density class
Polyethylene	PE	0.91	0.97	Low
Polypropylene	PP	0.90	0.91	Low
Polyester	Polyester	1.24	2.3	High
Polyethylene terephthalate	PET	1.37	1.45	High
Polystyrene	PS	1.01	1.04	Int.
Ethylene vinyl acetate	EVA	0.92	0.94	Low
Alkyd	Al	1.67	2.1	High
Polyvinyl chloride	PVC	1.16	1.58	High
Polymethyl methacrylate	PMMA	1.17	1.20	High
Polyamide (nylon)	PA	1.02	1.05	Int.
Polyacrylonitrile	PAN	1.09	1.20	High
Polyvinyl alcohol	PVOH	1.19	1.31	High

polymers were not significant for *ocean, sediment* and *freshwater, sediment* (Kruskal-Wallis rank-sum test: $P = 0.38$ and $P = 0.17$, respectively). Among compartments, only PA showed a significant difference (Kruskal-Wallis rank-sum test: $P = 0.05$), and the variation for the other polymers between compartments was not significant.

3.2. Product categories

Adequate and comparable data for product categories were difficult to obtain from peer-reviewed studies. Therefore, the data from two studies were compared. One study focused on epipelagic riverine plastic (van Emmerik et al., 2018), and one study on epipelagic ocean plastic (Lebreton et al., 2018) (Fig. 2). In the ocean study, 93% of plastics were

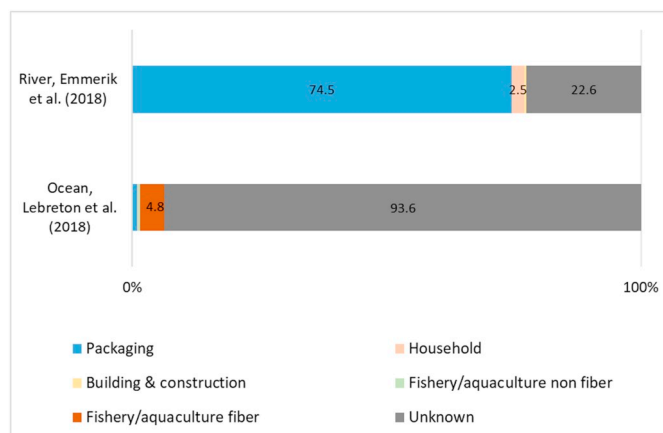


Fig. 2. Plastic litter composition in two different environments (ocean, epipelagic, and river, epipelagic), in percentages. The composition resembles the main production categories and the fishery and aquaculture materials separately. An unknown category was added for products that resembled a “fragment” or were identified as “unknown”.

Figure developed from data adapted to product categories from Lebreton et al. (2018) and van Emmerik et al. (2018).

classified as unknown, as a product category could not be attributed to most of these observations, which were in the study classified as “fragments”. From the identified portion, 4.8% were lines, nets, and ropes and 0.4% were non-fiber fishery and aquaculture items. Only 1.0% of items were identified as packaging. If only the identified portion is considered, over 80% of observed plastic waste originated from ocean-based sources. The river plastic product types observed differed from ocean plastics product categories. The unknown category made up 22.6%, while the lion share of plastic items was identified as packaging, 74.5%. Household and building and construction products were observed in the river compartment, 2.5% and 0.5%, respectively. For oceans, only 0.1% of items could be related to household as well as building and construction. Plastics from transport, electronics, and industry were not observed in any of the studies.

4. Discussion

4.1. Plastic transport in aquatic environments

Movement of plastics in the water, both in the vertical and in the horizontal dimension, is created through the characteristics of plastic waste and the local environmental factors. The vertical movement of plastics in water, or sedimentation rate, is mostly affected by three characteristics: the density, the surface area of the polymer, and the particle size (Chubarenko et al., 2016; Kowalski et al., 2016). The density of a polymer can be either higher or lower than water (with ocean density $1.02\text{--}1.04\text{ g cm}^{-3}$ and freshwater 1.00 g cm^{-3}). Several polymers remain buoyant in water, while other polymers sink, and yet another group has an intermediate density. Their sedimentation behavior depends more strongly on the local environmental factors (Table 2). The polymer PS occurs both foamed (expanded polystyrene or EPS) and non-foamed, but as this was not always explicitly mentioned in studies, the density of the polymer is difficult to determine. The effect of density is visible in polymer compositions in the epipelagic compartments. Here, the buoyant, low density polymers (PE and PP) were dominant, while high density polymers were rarely or not observed. Interestingly, rivers show a higher fraction of high density polymers than the ocean. This can be explained through higher current strength in rivers. Through this, turbulence increases and high density polymers remain buoyant and can hence be transported horizontally instead of vertically. A lower current strength in oceans may lead to the vertical transport to take over, which explains the difference in high

density polymer contribution. Studies also observed that the contribution of high density polymers decreases when moving away from the coastal areas (Pedrotti et al., 2016). On the other hand, a stronger turbulence forces sedimentation of low density plastics. This turbulence of water can be created through wind, waves and/or currents, and will result in additional vertical movement through the water column (Kukulka et al., 2012). This particularly affects smaller macroplastics and microplastics, which tend to have a lower terminal rising velocities as a result of their larger surface area (Kooi et al., 2016; Lebreton et al., 2018). Through this mixing, micro- and nanoplastics ($< 100\text{ nm}$) from low density polymers heteroaggregate with suspended solids, resulting in sedimentation in the top layer, which in models even reach 50% of total particles (Besseling et al., 2017). These particles can be re-suspended but also get buried in deeper sediments. The vertical movement, or sedimentation, is also affected by environmental factors. For example, in oceans, a lower ocean temperature and higher salinity result in an increase of high density polymers in the water column (Kowalski et al., 2016). In short, composition of plastics in the established compartment is strongly affected by polymer type, where variation in the composition within the same compartment is likely explained by variations in environmental factors such as salinity and temperature.

Furthermore, plastic particles with a high surface area, such as films and fibers, are likely to have a higher rate of sedimentation (Fazey and Ryan, 2016). This is mainly due to a higher exposed surface area. Therefore, a high rate of biofouling occurs on these particles which increases the density of the plastic (Chubarenko et al., 2016; Ryan, 2015). Defouling will occur after these particles sink, creating a loop where particles sink and resuspend over a period of time (Ye and Andrady, 1991). The rate of biofouling is strongly affected by environmental factors as well, as high temperatures and nutrients increase the rate of biofouling development. This is observed in several studies, as plastic fibers are more often than fragments encountered in oceanic sediments (Peng et al., 2018; Woodall et al., 2014). Additionally, most fibers retrieved from sediments are high density polymers, including PMMA, polyester, and polyamide (Sanchez-Vidal et al., 2018). Films are rarely observed in the epipelagic zone mid-ocean, meaning that these products are transported or retained elsewhere (Lebreton et al., 2018). Smaller macroplastics and microplastics tend to sink quicker than larger plastics, as their surface area-to-mass ratio decreases with size, making them more susceptible to biofouling (Fazey and Ryan, 2016). This is a likely explanation for the lower quantities of microplastics at the ocean surface (Cozar et al., 2014). In the end, only larger, thick-walled objects are likely to reach open oceans (Pedrotti et al., 2016). It is assumed that these plastics remain for a long time in the epipelagic zone of the ocean. This is supported by long exposure times for oceanic epipelagic plastics (> 30 months) (Brandon et al., 2016). This suggests that the select group of plastics reaching open ocean (large, low surface area, low density) persist and accumulate in the oceanic epipelagic zone. On the other hand, modeling studies show that biofouling processes lead to the sedimentation of these plastics within three years (Koelmans et al., 2017). This scenario is also very plausible, as the contribution of both PE and PP is high in ocean sediments, even though their density would suggest them to remain in the epipelagic zone. Therefore, it can be argued that the ocean epipelagic zone is only a temporary accumulation zone, while sediments are the likely final accumulation zone for all floating oceanic plastics (Koelmans et al., 2017).

The effect of windage on the horizontal transport of plastics has most effect on buoyant objects that extend above the water surface. This is particularly the case for foamed plastics, like EPS, or air-filled bottles and containers (do Sul et al., 2014). As a result, these objects are more affected by wind and are more likely to be moved horizontally, both faster and further, and are also more likely to be deposited on beaches and river banks. In various studies, EPS is observed in high frequencies on freshwater beaches (Corcoran et al., 2015; Faure et al., 2015). Especially during storms or oceanic high-tide events, plastic is

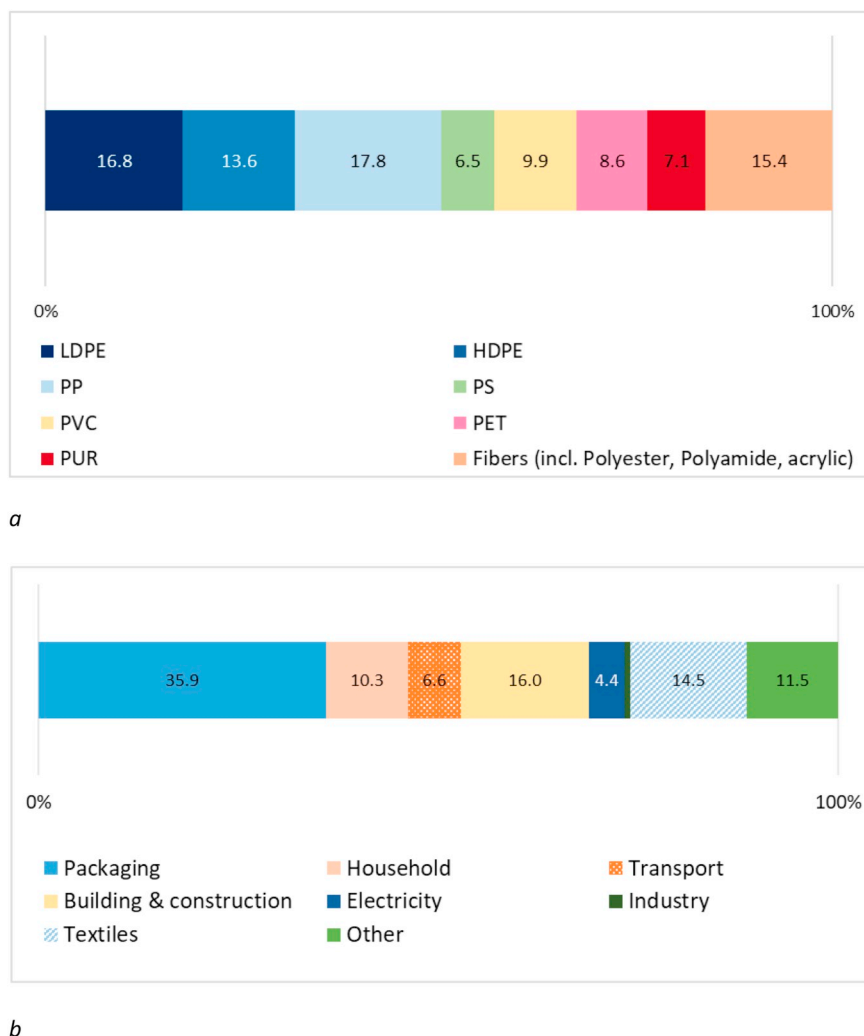


Fig. 3. a. Plastic production per polymer type, in percentages. Figure based on data that were collected by Geyer et al. (2017).
b. Plastic production divided per product category, in percentages. Figure based on data that were collected by Geyer et al. (2017).

likely exchanged between the established compartments, where high windage plastics are more affected than low windage plastic. Additionally, events with high precipitation, such as monsoons, may lead to a large flow of plastics from land to the different aquatic environments (Lebreton et al., 2017). Lighter plastics such as EPS, bottles, and films will be triggered earlier than larger and heavier plastic objects.

4.2. Product and plastic polymer contribution

Several product categories and polymers are overrepresented in the environment compared to the plastic production composition. For plastic categories, the production deviates strongly from environmental observations (Fig. 3a). Plastics from the categories transport and electricity are not observed in any aquatic environment, although their production quantities are significant (6.6% and 4.4%, respectively). Furthermore, building and construction items are rarely observed, while 14.0% of yearly plastic production is for this sector. Often, these items have a longer lifetime and therefore should contribute less than current production rates to plastic waste on a yearly basis (Geyer et al., 2017). Single-use products like packaging and household products are the main identified items observed in the oceans (15.9% when excluding the unknown fraction) and rivers (74.5%), while packaging is 36.0% of total production. In rivers, household items have the second largest contribution after packaging. However, the contribution to the environment (0.1% and 2.5%, respectively, in oceans and rivers) is

lower than the production (10.3%). Even though terrestrial studies are excluded, many litter reports show that packaging and consumer goods are overrepresented here; often, all categories can be related to packaging (Carpenter and Wolverson, 2017; Schultz and Stein, 2009). In the river sediments, most identifiable items can be allocated to packaging and household items (Morritt et al., 2014). Beach observations show a high contribution of these two categories as well, with additional items from aquaculture and fishing from ocean sources (Ocean Conservancy, 2019). Oceanic seabed studies show that a significant portion of items on the seafloor consist of fishery items and fibers, however also (industrial) packaging items are still present (Ioakeimidis et al., 2014; Lee et al., 2006; Pasquini et al., 2016). For the epipelagic ocean, > 80% of identified items were related to ocean-based activities (Lebreton et al., 2018). The same study concluded that nets and lines, made of synthetic fibers, represented > 50% of the total floating mass of plastics and were made of either the polymer PE or PP. This demonstrates that ocean plastics and river plastics are different from one another in terms of product categories. This suggests that the exchange of plastic waste between rivers and ocean is relatively low and that the plastic waste in these environments originates from two different sources. Overlap is likely in the coastal areas, with a reducing interaction between river and ocean when moving away from the coast. Hence, plastic waste from both land- and ocean-based sources is present at the ocean beach and ocean sediments close to the beach because of this interaction.

Differences between production and environment are also observed for plastic polymer composition. Compared to production data (Fig. 3b), PE and PS are more represented in the environment, while for PP and fibers (likely including polymers like PA, polyester, and PAN), the compositions are similar. Interestingly, PVC and PET are observed in lower quantities in the environment than the production composition.

Polymer compositions and product categories are linked, as different products can require different polymer properties (Geyer et al., 2017). Packaging and household plastics are often made of PP, PE, and PS, which are also the polymers with the highest contribution to composition in most aquatic environments. Interestingly, PET, also often used in packaging, has a lower contribution in all compartments, especially compared to PE and PP. In ocean sediments, the high contribution of polymers used in fiber-based plastics such as polyester, PA, and PAN can be linked to the fishing industry, as they use these synthetic fibers for their gear (Claessens et al., 2013; Peng et al., 2018). PE and PP are also represented in the fibers observed in the epipelagic ocean zone, suggesting that these polymers occur in fishing gear as well (Lebreton et al., 2018). Microfibers that come from clothing can end up in the environment through sewage (Pedrotti et al., 2016). This is most likely due to higher density, shape, and size in combination with biofouling. These microfibers will be observed in freshwater sediments or close to the coast, rather than in the epipelagic zone. Therefore, these fibers will most likely not be transported towards the open ocean. Accumulation of fibers will confirm this observation. Therefore, the fibers that are encountered in ocean sediments further from the coast will most likely originate from fishing gear, which are made mostly of the intermediate- to high-density polymers such as PA, PS, or PVA.

Lastly, the contribution of PVC in the environment is very low, especially compared to production (almost 10%). Interestingly, PVC is a polymer most used in building and construction. Factors such as larger sized objects used or better waste management for building materials are likely explanations for the lower contributions in the environment. A longer use phase for building materials will only explain a lower contribution to yearly waste than production.

Combining the observations of both product categories and polymers shows that specific types of plastic products are almost not represented in the environment. This includes plastics from electronic, building and construction, and transport applications. Most plastic waste in oceans originates from industrial coastal and ocean activities, mainly the aquaculture and fishing industry. On the other hand, in freshwater systems, plastics from packaging and household items dominate. Except for the ocean beaches, there is little overlap visible in plastic production categories of ocean and freshwater systems. This means that transport of plastics from river to ocean is low, and plastic waste is retained in rivers rather than transported to oceans. This is supported by modeling studies where the modeled riverine plastic quantities are higher than the modeled buoyant plastic quantities in the epipelagic zone of the ocean (van Sebille et al., 2015; Schmidt et al., 2017). It is therefore unlikely that riverine plastic waste is 100% transported to oceans, as this should result in higher quantities observed in oceans.

4.3. Plastic accumulation areas

Synthesizing studies on plastic litter results in the possibility to conceptually model the fate and accumulation zones of plastic once it enters the aquatic environment (Fig. 4). Plastic litter in ocean originates mainly from ocean-based sources. In this model, land-based sources contribute to a small amount through, for example, beach and river exchanges. Plastics from freshwater compartments all originate from land-based sources.

The properties size, shape, and polymer type of plastic waste are reported to be the main drivers for its transport. Environmental parameters such as salinity, wind and flow speeds, nutrients, and

temperature affect transport as well, creating regional differences. High density polymers, released into freshwater environments, sink to sediments in the freshwater system. Transport from freshwater sediments to ocean sediments occurs. However, the quantities are lower when comparing the transport through the water column because of lower flow speed. Polymers that are retained in river sediments, and potentially slowly transported, include PMMA, PVC, PAN, PVOH, and PET. PA and PS, which are most often used in fiber products, will also likely sink, but as their density is closer to that of water, the polymers are more likely transported through currents when turbulence is high. Low density polymers, which are either thin (films) or small (microplastics), are also likely retained in river sediments or in the lower water column because of biofouling and lower terminal rising velocities. This includes products from PE, PP, and EVA. Only thick-walled and larger PE, PP, and (E)PS particles are potentially transported from rivers to ocean. Plastic products that are highly affected by windage such as containers (for example PET bottles) and EPS are transported to river beaches. In oceans, the plastic waste originates from three main sources, namely, land-based plastics from coastal areas (Jambeck et al., 2015) and a select group of plastics from rivers together with plastics from oceanic sources. The higher density polymers from these sources will sink to the ocean sediments. This sinking will occur quite rapidly. Hence, high density land-based plastics will accumulate in sediments close to the shoreline. With storms, these polymers can be transported to the ocean beaches and back. Low density polymers (PP, PE, and EPS) will remain afloat for a certain amount of time and may be transported through currents towards the open ocean. Through biofouling, also low density polymers will eventually sink to ocean sediments and might (temporarily) resubmerge when defouled. Similar to rivers, the low density polymers with higher surface area including film material, fibers, and small plastics (microplastic) will sink to sediments sooner than larger and thicker fragments. Again, plastics highly affected by windage are likely to be transported to beaches or potentially to the open ocean.

4.4. Side notes to the study

This study combined individual plastic waste studies to obtain a dataset where plastic composition in the environment is put in a broader perspective. However, the individual studies were all inherently different in terms of goals and methodology, which can lead to a bias in the overview given here. For example, most polymer studies mainly focused on microplastics, and fewer studies included macroplastics (Table 1). It should be kept in mind that microplastics can be either primary or secondary and that primary microplastics have a different source compared to macroplastics and secondary microplastics, which can cause significant variations in polymer composition. Furthermore, variation in time, such as year and month of the study, and measurement methods were not taken into account. In particular, differences in measurement methodology can result in significant bias in sizes, shapes, and even polymer types (e.g., Reddy et al., 2006). As no settlement on a uniform method is yet accomplished, it was assumed the variations in methodology would not lead to significant differences in results unless explicitly mentioned in the studies themselves.

The plastic composition varied strongly among regions and even within compartments. Some of these variations were explained in the study, such as industrial activities (Zhao and Zhu, 2011). However, most variation is difficult to explain and not all variation can be addressed to environmental factors. Additionally, environmental variables such as storms and precipitation can affect the compositions on individual locations throughout time as well. To tackle local plastic pollution, global models will only be useful to obtain a broad overview, not for assessing and explaining local variations. A regionalized material flow analysis and details on environmental compartments can result in additional insight into regional plastic losses, transport pathways, and accumulation zones.

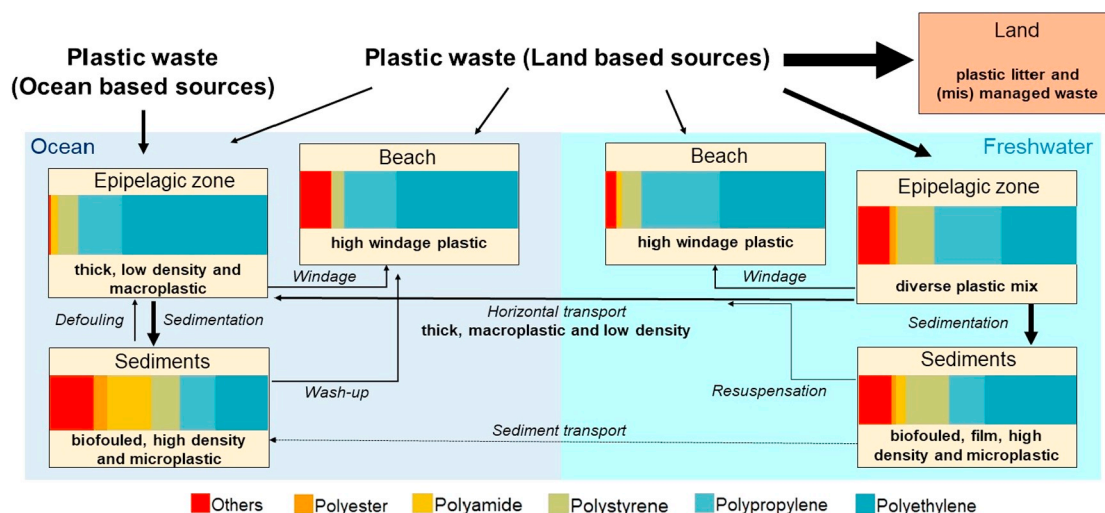


Fig. 4. A conceptual model containing the average polymer compositions in six different environmental compartments distinguished in this paper. Arrows indicate the main transport pathways and movement of material from one compartment to another. Thicker arrows show the main transport, whereas thinner arrows show lower movement.

5. Conclusion

The goal of this study was to identify plastic waste polymer types and product categories throughout different environmental compartments. In this study, variations in quantities and compositions were observed throughout the different environmental compartments, for both the composition of plastic polymers and product categories. In particular in epipelagic waters, polyethylene and polypropylene were mostly observed. However, in sediments, other polymers were observed in high proportions, including polyamide and polyester. Most studies found product categories are packaging products in rivers, while packaging products are only 36% of produced plastics. On the other hand, the fishery and aquaculture objects dominated in oceans. To reduce plastic litters in the aquatic environment, policymakers are therefore advised to focus on these industries. The variations that occur among the different compartments can be explained through the differences in density, surface area, and the size of products. Only thick-walled, larger plastic debris from low density polymers are potentially horizontally transported from rivers to ocean through currents. The exchange of plastic waste between rivers and ocean is therefore considered relatively low, and buoyant plastic waste in oceans and river originates largely from two different sources. Much of the plastic waste likely remains in river systems or is transported to beaches by wind. Hence, by linking together all individual studies on different aquatic sub-environments and regions, this unique and global view was obtained on plastic transport in aquatic environments and the potential accumulation zones in the environment. In future work, this study can be linked to quantitative studies to obtain a more detailed global plastic litter map that includes transport and accumulation. Next, these values can be linked to ecotoxicity and environmental studies to predict global damage from plastic waste, to be included in LCA studies.

CRediT authorship contribution statement

A.E. Schwarz: Methodology, Data curation, Formal analysis, Visualization, Writing - original draft, Writing - review & editing. **T.N. Ligthart:** Methodology, Supervision, Writing - review & editing. **E. Boukris:** Methodology, Writing - review & editing. **T. van Harmelen:** Methodology, Supervision, Visualization, Writing - review & editing.

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Declaration of interest

All authors declare no conflicts of interest.

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