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POSSIBILITIES TO PREVENT AND REMOVE MARINE LITTER

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ABSTRACT

Lappeenranta–Lahti University of Technology LUT
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Possibilities to prevent and remove marine litter

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Marine litter is a major global problem that affects not only the environment, but also the economy and the society. The main source of marine litter comes from land-based activities, of which a large quantity of land-based waste is transported via rivers into the seas and oceans. To tackle the inflow of litter into the marine environment this thesis focuses on marine litter in the riverine system. Numbers regarding the amount of plastic waste that is entering the ocean differs from various sources, although the yearly input of plastic waste reaching the ocean is millions of tonnes. In addition, to addres the main flows of plastic waste entering the ocean two lists of the 20 most polluting rivers are shown. Likewise, as the quantity of marine litter, these two lists have different outcomes. Furthermore, this report shows the current situation regarding riverine marine litter and which possibilities there are to prevent and remove marine litter. Although the possibilities to prevent marine littering are mentioned, the main focus of this thesis is the removal technologies for marine litter in rivers. Five different removal technologies have been outlined and these are compared by various specifications, operating conditions and costs. In addition, it is mentioned where the different removal technologies can be used best. This is done by using a scenario shown in a scheme.

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In Lappeenranta, Wednesday 10 November 2021

Jelmer de Vries

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LIST OF SYMBOLS

Symbols

€	Euro
%	Percent

Units

kg	kilogram
km	kilometer
mm	millimeter
m	meter
m^3	cubic meter
t	tonne

Abbreviations

ALDFG	Abandoned, lost, or otherwise discarded fishing gear
EU	European Union
LCA	Life-cycle assessment
LUT	Lappeenranta-Lahti University of Technology
MPW	Mismanaged plastic waste
MSW	Municipal solid waste
SUP	Single-use plastics
TRL	Technology readiness level

1 INTRODUCTION

Oceans contain roughly 97% of all the water on earth and represent more than two-third of the earth's surface (Roscam Abbing and Vork, 2019). These oceans are full of various species of marine life and rich biodiversity, in addition, they are an important factor in the earth's climate. Unfortunately, the marine environment is undergoing several global environmental problems, one of which is marine litter (also called marine debris). Marine litter is defined as manmade waste that is thrown away, disposed or left behind in the marine or coastal environment, including all waste that enters the sea indirectly (UNEP and GRID-Arendal, 2016). Marine litter appears in various forms and sizes, for example large (lost) sea containers, fishing nets, plastic packaging, cigarette buts and micro plastics. Approximately 80 per cent of the (plastic) marine litter originates from land-based sources, the remaining 20 per cent is caused by activities at sea (Roscam Abbing and Vork, 2019). Marine litter causes several local environmental problems. For instance, waste washing up on shores and beaches, the collection of waste in so-called 'garbage patches' in ocean gyres or sunken waste on the seafloor causing harm to seabed life e.g. coral reefs. All these activities have a devastating effect on marine life, biodiversity and humans.

The quantity of marine litter already in seas and oceans and new waste entering the marine environment is still unclear and debatable. However, plastic is the main contributor of waste on shorelines, the sea floor and on the sea surface, with an approximate share of 60-90% and in some cases even up to 100% (UNEP and GRID-Arendal, 2016). It's estimated that between 4.8 and 12.7 million tonne of plastic waste generated by land-based sources are entering the ocean per year (Jambeck *et al.*, 2015). Due to the slow degradation of the majority of the plastics, their presence in the marine environment can be for a long time. Plastic waste is affecting more than 260 species with possibly fatal results, for example, entanglement or ingestion of plastic (STAP, 2011). Another issue that is gaining more and more attention regarding marine littering are microplastics. According to NOAA (NOAA, 2021), microplastics are plastic particles that have a length smaller than 5 millimetres. These microplastics can be easily absorbed by marine animals that are part of the human diet. The impact that microplastics have on human health is still unclear and might be worse than we realise at the moment.

The goal of this study is to analyze marine littering and show how this environmental problem can be tackled. This will be done by mapping the cause of waste ending up in the marine environment and by mapping the main waste flows to oceans and seas globally. This study is not focusing on the first stages of prevention, like change in production and consumption, waste management and recycling. In this study, the focus will be on what can be done for waste that has already turned into riverine litter. Therefore this study will be mainly focusing on the removal methods and technologies to remove the litter before it reaches the sea and oceanic environment. Furthermore, the focus of this study is on waste from land-based sources in river pathways in for example rivers, stormwaters, wastewaters, canals, harbours and river mouths.

2 MARINE LITTERING

Marine littering is an environmental problem affecting the marine environment all over the world. Marine litter even reaches the remotest places on earth. But what is marine litter exactly? And what is the current situation with marine litter? And where does it come from?

2.1 What is marine litter?

According to Shevealy et al. (UNEP and NOAA, 2012) marine litter is defined as "any anthropogenic, manufactured or processed solid material (regardless of size) discarded, disposed of, or abandoned that ends up in the marine environment''. This definition can even be expanded by the following "including all materials discarded into the sea, on the shore, or brought indirectly to the sea by rivers, sewage, storm water, waves or winds".

Marine litter appears in various appearances, for example large (lost) sea containers, fishing nets, plastic packaging, cigarette buts and micro plastics. A common way to distinguish these waste items is by looking at the main material composition of the marine litter item. Some frequent materials of which marine waste items are made of are wood, paper, textiles, glass, metal, rubber, ceramics and plastic (UNEP and GRID-Arendal, 2016).

It is hard to get global numbers for the material composition of marine litter. This is because in different parts of the world the shares of waste items are different. In addition, the place where the measurements have been done can also make a difference. For example, measurements done from a coastal clean-up show different results compared to measurements taken from the seafloor. Furthermore, the literature is currently quantifying collected marine litter in different ways, by weight, item count or volume. Therefore it is also difficult to compare these results in a fair way (Schneider *et al.*, 2018).

Although the following *Figure 1* from Bergmann et al. (Bergmann, Tekman and Gutow, 2017) shows a diagram with the global material composition of marine litter. These values have been calculated by weighing the means of 711 different marine litter collections studies. The studies used for coming up with the global material composition considered locations in different parts of the world and litter on the seafloor, the water surface, on the beach and water column. Microplastics were not taken into account for the composition of marine litter, because contrasted to litter, microplastics consists exclusively out of plastic.

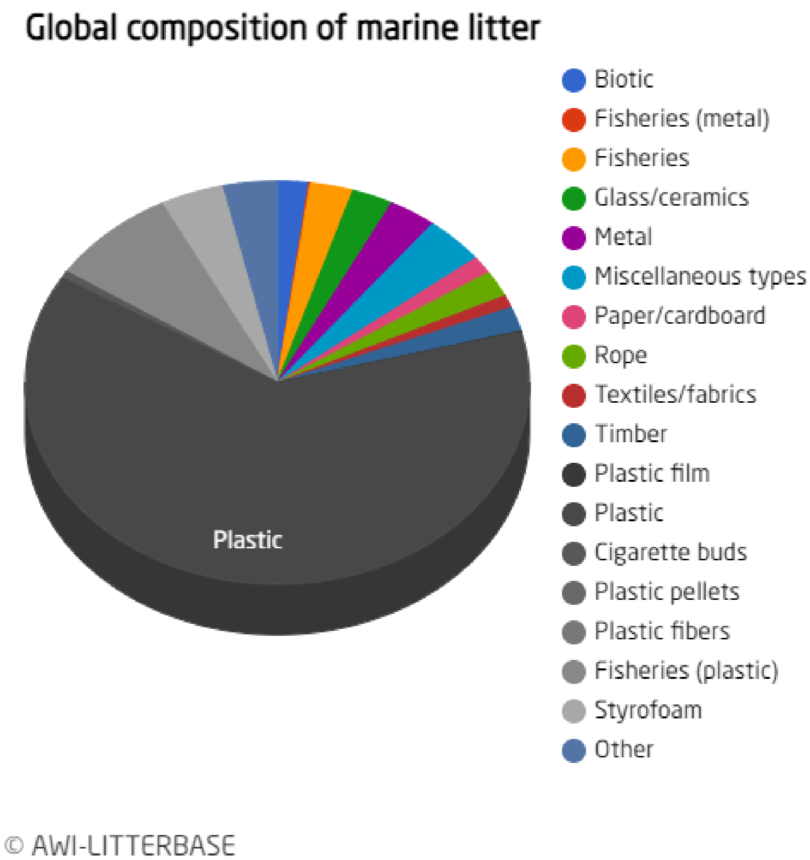

Figure 1 Global composition of marine litter (Tekman M. 2021)

Table 1 shows the exact percentage of the contribution of each litter type to the global material composition. As can be seen from the table underneath the most characteristic and well know marine litter material is plastic in all its various appearances. According to table 1, plastic accounts for more than 70% of all marine litter. In addition, according to the UNEP and GRID-Arendal (UNEP and GRID-Arendal, 2016) litter that is accumulating on the sea floor, sea surface, shorelines and beaches consists between 60 and 90 per cent out of plastic and in some cases it can be as much as 100 per cent.

Table 1 Contribution of different litter types (Bergmann, Tekman and Gutow, 2017)

Litter type	**Percentage (%)**
Plastic*	62.74
Plastic film	0.1
Plastic pellets	0
Plastic fibers	0.07

Fisheries	2.75
Fisheries (plastic)	8.12
Fisheries (metal)	0.09
Styrofoam	4.04
Textiles/fabrics	1.01
Rope	2.09
Paper/cardboard	1.41
Glass/ceramics	2.64
Metal	3.06
Cigarette buds	0.53
Timber	1.94
Miscellaneous types	3.85
Biotic	2.02
Other	3.54

*Other plastics, excluding the plastics mentioned below in the table

A study done about litter on the seafloor in European waters collected with video and trawl surveys over 32 different sites shows that the composition of litter mainly consists of plastic with 41%, followed by derelict fishing gear with 34%. Derelict fishing gear is mainly made of plastic, but in this study, it was shown as a free-standing litter category because of its social implications and impacts. The other litter items represented were metal, glass, clinker and "other items" which accounted for respectively 7, 4, 1 and 13%. The category "Other items" includes wood, paper/cardboard, clothing, pottery and unidentified materials (Pham *et al.*, 2014).

2.2 Current situation

Nowadays marine litter is getting a lot of attention, particularly plastic waste in oceans and seas. From time to time the news is showing articles related to marine litter and the environmental impact it has. Furthermore, there have already been done several pieces of research about this topic. Although these days the media and researchers are more looking at the more concerning effect of microplastics and their effects on the environment and humans. Since marine litter is a 'hot' topic more and more research will be done to hopefully end this problem.

According to the UNEP (UNEP, 2005), the two main impacts of marine litter on wildlife are entanglement and ingestion. There have been multiple reports regarding incidents of entanglement and ingestion for a wide range of fish, reptiles, birds and marine mammals, examples can be seen in *Figure 2* (STAP, 2011). In the majority of the cases entanglement leads to an acute and chronic injury, which leads to increased mortality or it directly leads to death. When it comes to ingestion, marine animals can mistake plastic litter for their natural food, which then ends up in their guts. For some marine animals, it is very difficult to eliminate the litter item once it is ingested (UNEP, 2016).

Figure 2 Entangled turtle (A), entangled seal (B) and a Laysan albatross carcass with plastic (C). (STAP, 2011)

Besides harming the wildlife marine litter can also damage habitats. Due to winds and tidal currents the movement of abandoned, lost, or otherwise discarded fishing gear (ALDFG) can cause damage to coral reefs. Furthermore, mangrove forests can become a sink for plastics, since marine litter tends to collect in mangroves (UNEP, 2016).

It is proven that the consumption of marine food exposes humans to micro- and nano plastics. The existence of microplastics causes a threat to food safety, although there is a knowledge gap regarding the effect and toxicity of microplastics in humans (Smith *et al.*, 2018). Furthermore, human health and safety can be directly affected by marine litter in multiple ways. For instance, navigational hazards due to marine litter can cause boats to disable and the passengers to be marooned. Secondly, submerged litter can be dangerous for swimmers and divers, since they can get entangled. Thirdly, marine litter that appears on shores, beaches and shallow waters can lead to injuries to beach goers. Lastly, especially medical and sanitary waste can contaminate water, which can have a direct impact and an indirect impact by consuming contaminated food (UNEP and NOAA, 2012).

Marine litter does not only affect the society and the environment, but it also has an impact on the economy. Negative economic and financial impacts can be experienced by governments, local communities and the fishing, tourism and transportation sectors (STAP, 2011). As for the effects on tourism, marine litter affects recreational places like beaches or recreational activities like diving. The appearance of marine litter can bother visitors and prevent them from visiting. This has a negative impact on tourism in a certain area and so also on the local and regional economy. In addition, marine litter can cause economic costs in the fishing and transportation sectors for example due to the following actions: damage from marine litter due to collision or entanglement in the commercial shipping sector, the loss of cargo in the marine environment can lead to compensation payments and ghost fishing from ALDFG causes loss of the desired catch (UNEP, 2016).

At this point, it is clear that marine litter has significant negative effects on the marine environment, which in correlation affects the economy and the society. Although the complete impact of litter on the marine environment is still unfamiliar and, for that reason, it is hard to adequately assess the economic and social costs (UNEP and GRID-Arendal, 2016).

2.3 Quantity of marine litter

The total amount of marine litter in the marine environment at the moment is unclear, there are no certain figures regarding the marine litter situation worldwide. This has to do with the fact that marine litter appears in waters all over the world and even in the most remote places. In addition, there are a lot of nano and micro waste particles which are difficult to see and consequently difficult to measure and map. Due to this, it is hard to measure every waste item globally and therefore it is almost impossible to determine the total amount of marine litter in the oceans and seas. Several studies give an estimate of the plastic litter which is entering the marine environment, four of these studies will be described further.

According to a study done by Jambeck et al (Jambeck *et al.*, 2015), the plastic waste generated by land-based sources entering the ocean is estimated to be between 4.8 and 12.7 million tonne per year. This study combined the global data on solid waste, the economic status and the population density to determine the number of plastic waste entering the ocean from 192 coastal countries. For this study, the estimation of municipal solid waste (MSW) generated by the 192 coastal countries is 2.5 billion tonne. From this, it is estimated that 95.5 million tonne of plastic waste are generated by people living within 50km of the coast. Whereof 31.9 million tonne were classified as mismanaged plastic waste and from that 4.8 to 12.7 million tonne of plastic enters the oceans. This corresponds respectively to 0.19%

and 0.51% of the total generated MSW by the 192 countries. It has to be noticed that only land-based sourced waste from the coastal population has been taken into account, this means that the waste is not only transported by rivers, but also from direct litter transported by wind or tidal.

A study done by Lebreton et al. (Lebreton *et al.*, 2017) estimates that between 1.15 and 2.41 million tonne of plastic emissions enter the world's oceans every year. This study considers population density, mismanaged plastic waste (MPW) production rates per inhabitant per country, monthly catchment runoff and the appearance of artificial barriers. In addition, the study estimates that Asian rivers are accountable for around 86% of the global riverine plastic pollution. This is mainly caused due to the high-population density together with high production rates of MPW and periods of excessive rainfall.

Another study done by Schmidt et al. (Schmidt, Krauth and Wagner, 2017) estimates a plastic waste input to the sea that ranges from 0.41 to 4 million tonne every year. This study is in line with the study done by Lebreton et al. (Lebreton *et al.*, 2017). The reason why these two studies have a relatively similar outcome is that both studies use the same MPW data set and partly use the same data regarding plastic in rivers.

According to a recent study conducted by Meijer et al. (Meijer *et al.*, 2021), the global riverine plastic emissions into the ocean is estimated to be between 0.8 and 2.7 million tonne annually. The model used to calculate the probability of plastic waste reaching the river includes geographically distributed data on plastic waste, wind, land use, rivers and precipitation. Furthermore, this study estimate that more than 1000 rivers are responsible for 80% of the global plastic emissions. In addition, this study estimates that 1.5% of the total generated MSW is entering the ocean within a year.

Table 2 Estimations of plastic waste inputs into the marine environment from different studies

Study (author and year)	Estimation of global annual plastic waste input into seas and oceans	Notes
Plastic waste inputs from land into the ocean (Jambeck *et al.*, 2015)	4.8 – 12.7 x 10^6 t	Land-based sourced plastic waste from 192 coastal countries. Not defined if the plastics are micro, macro or both.

River plastic emissions to the world's oceans (Lebreton *et al.*, 2017)	1.15 – 2.41 x 10^6 t	Plastic waste emissions from rivers. Micro and macro plastics (litter size spectrum: larger than 0.3mm to smaller than 0.5m)
Export of plastic debris by rivers into the sea (Schmidt, Krauth and Wagner, 2017)	0.41 – 4 x 10^6 t	Plastic waste emissions from rivers. Micro and macro plastics
More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean (Meijer *et al.*, 2021)	0.8 – 2.7 x 10^6 t	Plastic waste emissions from rivers, only macro plastics

There is a range of different numbers regarding the total amount of plastic marine litter entering the marine environment. These different numbers are shown in *Table 2*. Where one number gives an estimation of land-based plastic waste input into the oceans, the other three numbers give an estimation of the plastic waste input into the ocean from rivers. When looking at the numbers regarding riverine plastic waste input, the mean of those three numbers will become between 0.79 and 3.04 million tonne of waste entering the ocean from rivers. Note, this number only gives an estimate for the plastic waste reaching the ocean via rivers. The number from Jambeck et al. (Jambeck *et al.*, 2015) gives an estimated number for the plastic waste reaching the ocean from land-based sources. The land-based plastic waste input is fairly higher than the numbers from plastic waste input via rivers. This can be explained by the fact that land-based source plastic waste does not only come from rivers, but also come from other land-based waste pathways (e.g. stormwater runoff, littering and wind dispersal).

Furthermore, for all of the estimations mentioned above the waste entering the marine environment is plastic waste. Although plastic is the main contributor to marine litter it can be assumed that the total number of marine litter, with all the different litter items, will be even higher.

2.4 Sources of marine littering

Main sources of marine litter can be divided into activities from land-based and sea-based waste sources. The approximate ratio is 80 to 20 for land-based against sea-based. This ratio should be interpreted carefully since the ratio is not the same all over the world. In some parts of the world, the sea-based waste sources are overtaking the land-based waste sources (UNEP and GRID-Arendal, 2016).

2.4.1 Land-based

Land-based origin relates to littering activities caused directly on land. This litter can enter the marine environment straight from the coastline for example waste from recreation on the beaches or waste can come from (far) inland towns and industries whereby the waste is transported in waterways for example rivers and sewage and drainage (Mira Veiga *et al.*, 2016). Any kind of littered material can enter waterways due to precipitation, melting snow or (heavy) winds. In addition, the occurrence of hurricanes, tsunamis, storms and other natural events can transport a considerable amount of waste from the coastal area to the marine environment (UNEP and NOAA, 2012).

Land-based sources of marine litter are coming from mistreatment of solid waste materials, these can be both legal and illegal activities. Sources of land-based marine litter can be one of the following activities: badly managed landfills and waste dumps and industry sites, littering on land, poorly covered waste containers and waste transport, sewage treatment and overflows and dumping of industrial and domestic waste (UNEP and NOAA, 2012). Waste coming from land-based sources is highly affected by the waste management in a certain area. Areas with effective waste management would generally have less land-based waste, and so areas with no or improper waste management will most likely have a lot of land-based waste (Lebreton and Andrady, 2019).

2.4.2 Sea-based

Sea-based origin relates to litter that has entered seas and oceans intentionally or unintentionally due to human maritime activity. Sources of sea-based marine litter can be one of the following common marine activities: recreational and industrial fishery, cargo shipping, offshore energy facilities (e.g. oil and gas platforms), aquaculture installations, military vessels, cruises and ferries. This sea-based waste can include things like ALDFG, dumped (plastic) waste, lost or damaged vessels, cargo (e.g. sea containers) and aquaculture equipment (UNEP and NOAA, 2012).

Bad weather, storms and rough seas increase the probability of accidental loss of fishing gear, cargo or equipment into the marine environment. Likewise to the land-based sources, the occurrence of natural events can lead to a considerable amount of waste entering from sea-based sources into the marine environment. For example, losing sea containers is more likely to happen during extreme weather than during normal weather circumstances.

2.4.3 Pathways

Litter is finding its way to the marine environment via pathways from the source. Pathways are sometimes hard to distinguish from sources themselves. Although sources can be seen as the activities that create littering and pathways can be seen as the means or the ways in which litter is transported into the marine environment (Moora and Piirsalu, 2016). For land-based sources, the pathway of litter can be waterways (e.g. rivers or canals), wind, wastewater effluent or direct littering. As for sea-based sources, direct littering is seen as the main significant pathway. *Figure 3* shows the pathways and the fluxes of plastic waste into the ocean. The numbers shown in *Figure 3* are taken from Jambeck et al. (Jambeck *et al.*, 2015) and so only represent the plastic waste coming from land-based sources within a 50km coastal zone (UNEP and GRID-Arendal, 2016).

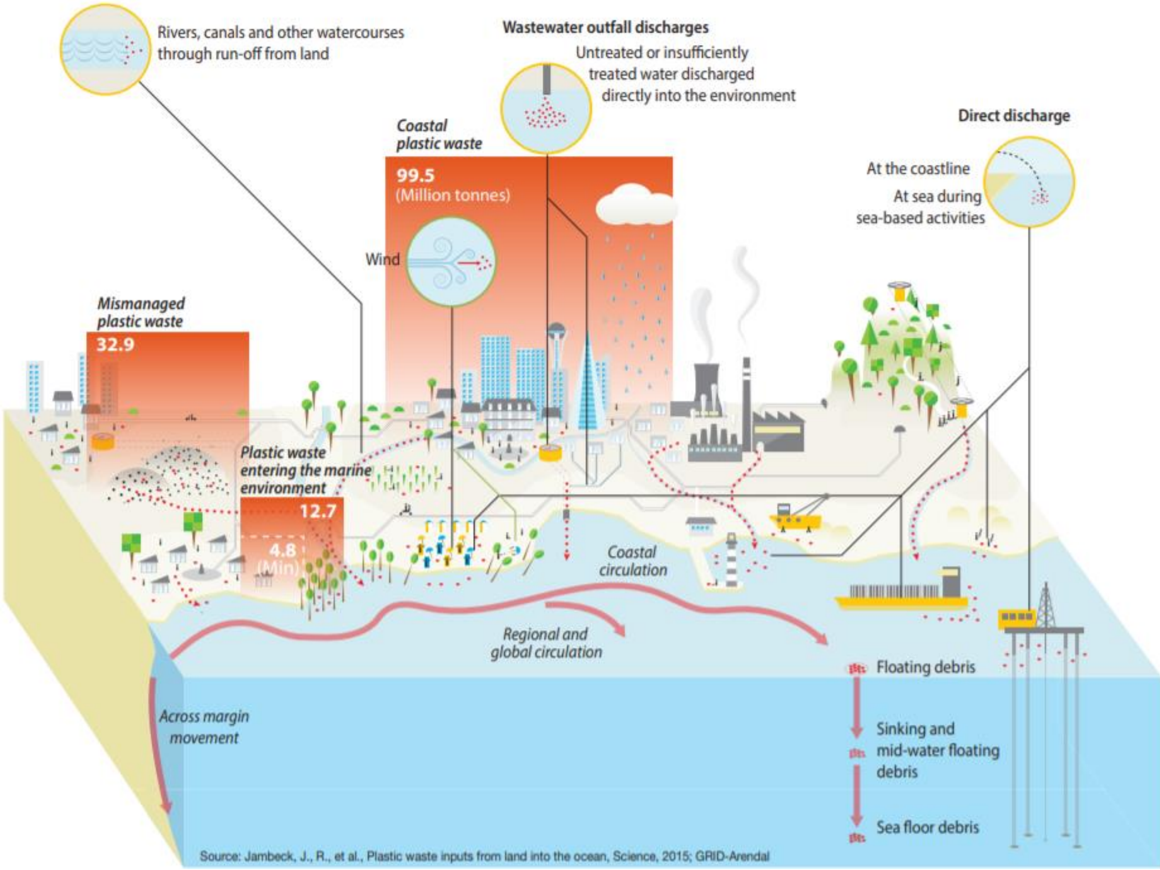

Figure 3 Pathways of plastic litter into the ocean (UNEP and GRID-Arendal, 2016)

It is assumed that much more plastic litter is transported by rivers than by wind. However, the input into the wind pathway has been investigated much less. Nevertheless, the transport of plastic litter by wind can play a substantial role in especially arid and semi-arid areas with lower surface run-off and with dry and windy conditions. In addition when the collected sewage is not treated properly or at all, the litter will enter the environment. Therefore wastewater effluent can be an essential pathway for plastic litter to enter the riverine and marine environment. The direct discharge of litter which is coming from sea-based sources is an essential pathway for coastal regions and the ocean (UNEP and GRID-Arendal, 2016).

2.5 Main waste flows

This chapter will show which rivers catchments transport the main flows of waste that are ending up in seas and oceans and what their estimated impact amount of waste per year entering the seas and oceans.

As mentioned in chapter 2.2, Lebreton et al. (Lebreton *et al.*, 2017) estimate that between 1.15 and 2.41 million tonne of plastic enter the world's oceans every year. Furthermore, this study shows the 20 most polluting rivers, which are responsible for more than two-third of the global plastic input. *Table 3* shows the 20 most polluting river catchments (Lebreton *et al.*, 2017). The estimated number of plastic pollution entering the oceans from each river is shown here as the midpoint estimates from the Lebreton study, these are shown in column 2. Column 3 shows the range of the plastic pollution from each river that is entering the oceans.

Table 3 20 most plastic polluting river catchments (Lebreton *et al.*, 2017)

River catchment (country)	**Estimated plastic mass input (tonne per year)**	**Range of plastic mass input (tonne per year)**
1. Yangtze (China)	0.333×10^6	$0.310 \times 10^6 – 0.480 \times 10^6$
2. Ganges (India and Bangladesh)	0.115×10^6	$0.105 \times 10^6 – 0.172 \times 10^6$
3. Xi (China)	0.739×10^5	$0.646 \times 10^5 – 1.140 \times 10^5$
4. Huangpu (China)	0.408×10^5	$0.335 \times 10^5 – 0.673 \times 10^5$
5. Cross (Nigeria and Cameroon)	0.403×10^5	$0.338 \times 10^5 – 0.605 \times 10^5$
6. Brantas (Indonesia)	0.389×10^5	$0.323 \times 10^5 – 0.637 \times 10^5$
7. Amazon (Brazil, Peru, Columbia and Ecuador)	0.389×10^5	$0.322 \times 10^5 – 0.638 \times 10^5$
8. Pasig (Philippines)	0.388×10^5	$0.321 \times 10^5 – 0.637 \times 10^5$
9. Irrawaddy (Myanmar)	0.353×10^5	$0.297 \times 10^5 – 0.569 \times 10^5$
10. Solo (Indonesia)	0.325×10^5	$0.265 \times 10^5 – 0.541 \times 10^5$
11. Mekong (Thailand, Cambodia, Laos, China, Myanmar and Vietnam)	0.228×10^5	$0.188 \times 10^5 – 0.376 \times 10^5$
12. Imo (Nigeria)	0.215×10^5	$0.175 \times 10^5 – 0.361 \times 10^5$
13. Dong (China)	0.191×10^5	$0.157 \times 10^5 – 0.317 \times 10^5$
14. Serayu (Indonesia)	0.171×10^5	$0.133 \times 10^5 – 0.299 \times 10^5$
15. Magdalena (Colombia)	0.167×10^5	$0.129 \times 10^5 – 0.295 \times 10^5$
16. Tamsui (Taiwan)	0.147×10^5	$0.116 \times 10^5 – 0.254 \times 10^5$
17. Zhujiang (China)	0.136×10^5	$0.109 \times 10^5 – 0.231 \times 10^5$
18. Hanjiang (China)	0.129×10^5	$0.103 \times 10^5 – 0.219 \times 10^5$
19. Progo (Indonesia)	0.128×10^5	$0.980 \times 10^4 – 0.229 \times 10^5$
20. Kwa Ibo (Nigeria)	0.119×10^5	$0.929 \times 10^4 – 0.208 \times 10^5$
Total:	$\mathbf{9.5 \times 10^5}$	$\mathbf{8.3 \times 10^5 – 14.7 \times 10^5}$

As mentioned in chapter 2.2, Meijer et al. (Meijer *et al.*, 2021) estimate that the global riverine plastic emissions into the ocean are between 0.8 and 2.7 million tonne annually. This study has also a list of the most plastic emitting rivers, the top 20 of this list is shown in *Table 4*. Column 2 in Table 4 shows the estimated yearly plastic mass input of each river and column 3 shows the range of plastic mass input, which is a factor 10 more or less compared to the estimated number. This factor comes to life due to the fact that it is important to consider that the emission values from individual rivers may vary from field observations up to a factor of 10.

Table 4 20 most plastic emitting river catchments (Meijer *et al.*, 2021)

River catchment (country)	Estimated plastic mass input (tonne per year)	Range of plastic mass input (tonne per year)
1. Pasig (Philippines)	0.63×10^5	$0.63 \times 10^4 - 0.63 \times 10^6$
2. Tullahan (Philippines)	0.13×10^5	$0.13 \times 10^4 - 0.13 \times 10^6$
3. Ulhas (China)	0.13×10^5	$0.13 \times 10^4 - 0.13 \times 10^6$
4. Klang (Malaysia)	0.13×10^5	$0.13 \times 10^4 - 0.13 \times 10^6$
5. Meycauayan (Philippines)	0.12×10^5	$0.12 \times 10^4 - 0.12 \times 10^6$
6. Pampanga (Philippines)	0.93×10^4	$0.93 \times 10^3 - 0.93 \times 10^5$
7. Libmanan (Philippines)	0.71×10^4	$0.71 \times 10^3 - 0.71 \times 10^5$
8. Ganges (India)	0.62×10^4	$0.62 \times 10^3 - 0.62 \times 10^5$
9. Rio Grande de Mindanao (Philippines)	0.53×10^4	$0.53 \times 10^3 - 0.53 \times 10^5$
10. Agno (Philippines)	0.46×10^4	$0.46 \times 10^3 - 0.46 \times 10^5$
11. Agusan (Philippines)	0.46×10^4	$0.46 \times 10^3 - 0.46 \times 10^5$
12. Paranaque (Philippines)	0.44×10^4	$0.44 \times 10^3 - 0.44 \times 10^5$
13. Iloilo (Philippines)	0.42×10^4	$0.42 \times 10^3 - 0.42 \times 10^5$
14. Soai Rap (Vietnam)	0.41×10^4	$0.41 \times 10^3 - 0.41 \times 10^5$
15. Chao Phraya (Thailand)	0.40×10^4	$0.40 \times 10^3 - 0.40 \times 10^5$
16. Lagos Harbour (Nigeria)	0.40×10^4	$0.40 \times 10^3 - 0.40 \times 10^5$
17. Hugli (India)	0.39×10^4	$0.39 \times 10^3 - 0.39 \times 10^5$
18. Huangpu (China)	0.36×10^4	$0.36 \times 10^3 - 0.36 \times 10^5$
19. Pazundaung Creek (Myanmar)	0.36×10^4	$0.36 \times 10^3 - 0.36 \times 10^5$
20. Bharathaoouzha (India)	0.35×10^4	$0.35 \times 10^3 - 0.35 \times 10^5$
Total:	$\mathbf{18.6 \times 10^4}$	$\mathbf{18.6 \times 10^3 - 18.6 \times 10^5}$

As can be seen from the upper two tables, the top 20 most polluting rivers and the plastic mass input of the top 20 rivers from the two studies are different. This is mainly because Meijer et al. (Meijer *et al.*, 2021) predict that plastic emissions are distributed over a larger number of mainly small urban rivers, estimating that 1656 rivers account for 80% of the global annual pollution. In contradiction, Lebreton et al. (Lebreton *et al.*, 2017) predict that plastic emissions are mostly generated by a top 122 (large) rivers which account for more than 90% of the total pollution. Meijer et al. (Meijer *et al.*, 2021) consider within a river basin a spatial variability of MPW generation. In addition, climate and terrain characteristics were introduced to differentiate the probability of leaking waste into the rivers and thereafter into the ocean. As a result there is a lower probability of MPW entering the ocean when the MPW is far upstream in a river basin. On the other hand there is a relative high probability of MPW entering the ocean when MPW is near a river and the coast. Taking into account these parameters, small river basins contribute relatively more than large river basins when having equal generation of MPW within the river basins. In comparison, in the study done by Lebreton et al. (Lebreton *et al.*, 2017), the MPW was just combined within a river basin, without taking into account the parameters mentioned above. This leads to unbalanced high predictions of plastic emissions in large rivers, while smaller rivers might have been underestimated.

Another observation that can be seen from the two tables shown in this subchapter, is that the majority of the rivers in both lists are located in Asia. Therefore it is of great importance that especially in this region the pollution of rivers should be tackled. Although Asia has the most rivers in the 20 list, that doesn’t mean that rivers outside the top 20 can be forgotten. Many other polluting rivers in continents like Africa and South America should not be left aside, also there the litter problem should be tackled.

3 POSSIBILITIES TO PREVENT MARINE LITTERING

Prevention means preventing waste from entering the oceans and seas and tackling the root causes of the pollution. Prevention of marine littering at the source is the key solution for this global problem, until that is fully realised the removal of marine litter is still highly important. Therefore this study will mainly focus on the removal of marine litter (chapter 4) to prevent litter from reaching the marine environment.

3.1 Awareness and behaviour change and clean-up projects

The generation of marine litter can be avoided with the help of activities regarding awareness-raising among customers, retailers and distributors. Awareness-raising campaigns should be wide-ranging and focused on the costs and the benefits of the action. In addition, the focus of the awareness-raising campaigns should be on businesses and citizens and should take into account gender, race age and class (UNEP and GRID-Arendal, 2016).

Raising awareness is needed and can be done in several ways and for different people groups. An example of an awareness-raising activity is cleanup projects. Clean up projects are happening all over the world and are increasing the concern of the environmental problem that marine litter causes. The yearly International Coastal Cleanup is a clean-up project which is happening in 127 countries. During this cleanup millions of people voluntarily pick up litter on beaches. In addition, the collection data is being recorded, which is giving information for a global database regarding marine litter (Weis, 2015).

More amateur beach clean-up projects and organised beach surveys are of importance to educate and engage local communities, stakeholders and media to raise awareness and expand knowledge on the problems arising from marine litter. With this as a starting point, a political boost can be established for implementing actions regarding controlling and managing marine litter better (UNEP, 2005).

Despite every action to improve waste management or legislation to ban single-use plastic, the marine environment will never be absolutely clean unless there is a major change in human mindsets and behaviour change about littering and producing less waste. Solutions for behaviour change strive to influence people's behaviour in such a way that they participate in activities that at least reduce the amount of waste, but even better remove or eliminate waste (Williams and Rangel-Buitrago, 2019).

Informing people about marine litter and its impact by formal education and more informal actions is a major step towards behaviour change and more awareness to protecting the marine environment. This education and actions are for all ages, but are commonly focused on school-age students. This is done hoping that their attitudes will remain and that they may have an influence on their generation and elderly people (UNEP, 2016).

3.2 Bans and economic incentives

Bans of products or activities, for example respectively a ban on plastic bags or a ban on smoking on beaches, can be a solution to avoid marine litter. Although the usefulness of bans depends on several factors for instance the political will, the availability of substitutes and competitiveness concerns (UNEP and GRID-Arendal, 2016). An example is the ban on single used plastics (SUP) in the EU. SUP accounts for around 49% of all the plastic that is found on European beaches (European Commission, 2018). Therefore the European Parliament approved a new law that is banning single-use plastic items. By 2021 the following products will be banned: single-use plastic cutlery and plates, plastic straws, plastic made cotton bud sticks, plastic balloon sticks and oxo-degradable plastics and expanded polystyrene cups and food containers (European Union, 2019).

Another method of prevention is economic incentives like charges for plastic bags or deposit refunds on bottles. In this way, the consumer's choice can be influenced and at the same time different habits can be encouraged like returning bottles or using a multi-use bag. Therefore incentives can operate as a useful and effective upstream method, which will lead to the reduction of consumption, less waste and an increase of recycling (UNEP and GRID-Arendal, 2016).

3.3 Research and innovation

An increase of research and innovation is needed to tackle (plastic) marine litter. To begin with, more research about the drivers, sources, status and impacts is needed to implement development and improvement of the existing policies, legislations and methods. Furthermore, research and innovation are needed to improve product design, waste prevention processes, recycling and increase resource efficiency. Especially researching the design options for plastic and plastic products can help reach a more sustainable economy (UNEP and GRID-Arendal, 2016).

An example is the use of degradable and compostable plastics, this should be encouraged more. Degradable plastics break down quicker, this is because it uses alternative materials or specialized enzymatic or chemical reactions which accelerates the breakdown process. Using degradable plastics brings along many benefits, for instance saving energy, reducing waste, reducing source material and allowing the use of plastic-eating bacteria (Williams and Rangel-Buitrago, 2019).

3.4 Improvement of waste management

According to a study conducted by Lebreton & Andrady (Lebreton and Andrady, 2019), two efficient ways can be used in the future to reduce the release of plastic litter into the marine environment. First of all, the waste management infrastructure should be improved together with an improvement of the capacity to recycle waste. This would be greatly crucial for China and India since currently respectively 70 and 85% of municipal waste is mismanaged in these countries. Secondly, introducing a limitation on the fraction of plastic in solid waste per capita, due to the decrease in demand for SUP. A reduction to a third of the current level could be reached when the plastic fraction in municipal solid waste is capped to 10% by 2020 and 5% by 2040.

In addition, to improve the waste management infrastructure, improving the wastewater treatment facilities can also avoid the distribution of litter in the marine environment. This can be done by investing in litter traps and microfiber filters for wastewater treatment plants (UNEP and GRID-Arendal, 2016).

3.5 Circular economy

Changing the current economic system from a linear economy to a circular economy will help to prevent the generation of marine litter. A linear economy is built on a high material demand, which is not sustainable from a social, economic and environmental point of view. Therefore the linear economy is not an option anymore and should be shifted to a circular economy. A circular economy stands for an economic system in which products, parts and materials keep their value as much as possible. This is done by applying approaches like reusing, refurbishing, recycling and remanufacturing. The purpose of circular economy in relation to marine litter is to achieve maximum value from all materials and to reduce, or even better, to eliminate waste in the marine environment. The shift to a circular economy is not only intended to decrease negative impacts, but also it stands for a systemic change in human behaviour. This change can create resilience for the long-term, bring forth new opportunities for the economy and provide benefits for the society and the environment (Williams and Rangel-Buitrago, 2019).

During a product's lifetime, environmental impacts can occur in all of the product's lifetime stages. The design phase is the phase where technologies, materials and product lifetimes are determined. Therefore this phase has an essential influence on the life cycle of the product and thus the environmental impacts coming along with that. That is why during the early phase of product development the environmental impacts from a product can be minimized or even avoided. For that reason, it is important that during the design and production of a product the environmental concerns are taken into account carefully and systematically, with a focus on value creation for customers and consumers (Williams and Rangel-Buitrago, 2019).

A tool that can be used as a guide for promoting a more sustainable production is life-cycle assessment (LCA). LCA can be used as a basis for decision making regarding the optimal use of resources and the effects of materials, processes or products on the environment. Therefore LCA should not only be limited to economic considerations, but should also consider social and ecological consequences of the production, use and disposal. Without evaluating the ecological and social perspectives in a comprehensive LCA approach, the decision made from the results can lead to excessive or unnecessary costs, ineffective mitigation measures or unexpected negative consequences. Furthermore as always with a LCA study, it is of big importance that before drawing any conclusions about the validity and the applicability of the study, the scope, assumptions, motivations, data quality and uncertainties are being considered (UNEP, 2016).

4 POSSIBILITIES TO REMOVE MARINE LITTER

In this chapter, different technologies and methods to remove marine litter will be reviewed. The focus will be on the removal methods and technologies for waste in all parts of the riverine pathway so that it can prevent that the waste from reaching the marine environment. This means from the beginning of the pathway where the waste enters the river like stormwaters and wastewaters, until where the waste exits the rivers like river basins, ports and harbours and all parts of the rivers in between like canals, side rivers and the main river. From all the technologies that will be reviewed in this chapter, the following specifications will be explained when available: the working method, the removal efficiency, (removal) capacity, costs, the best operational site, the strengths and weaknesses of the technologies and the development phase in which the technology currently is.

It should be noted that there are several solutions from different companies or organisations which have a similar working method or have a technology that appears to be almost the same as others. Due to that, this report will only describe the technology by one company or organisation and won't describe technologies which are quite similar.

At the end of this chapter, the different removal technologies will be compared to each other with some of the explained specifications. Furthermore, a scenario will be shown in which the technologies could be used to prevent litter from entering the marine environment.

4.1 TrashTrap

TrashTrap is a netting system trash removal solution by StormTrap. The purpose of StormTrap's solutions is to remove pollutants from stormwaters and wastewaters before the stormwater or wastewater reaches rivers, lakes and oceans. The TrashTrap technology uses the natural energy of water flow with disposable nets to catch and remove trash, solids and floatables easily from stormwater and wastewater. The TrashTrap systems are adaptable to a variety of applications there is an availability of several net size combinations. StormTrap offers three standard configurations which are shown in *Figure 4*, the in-line module, the end-of-pipe module and the floating module (StormTrap, 2020a).

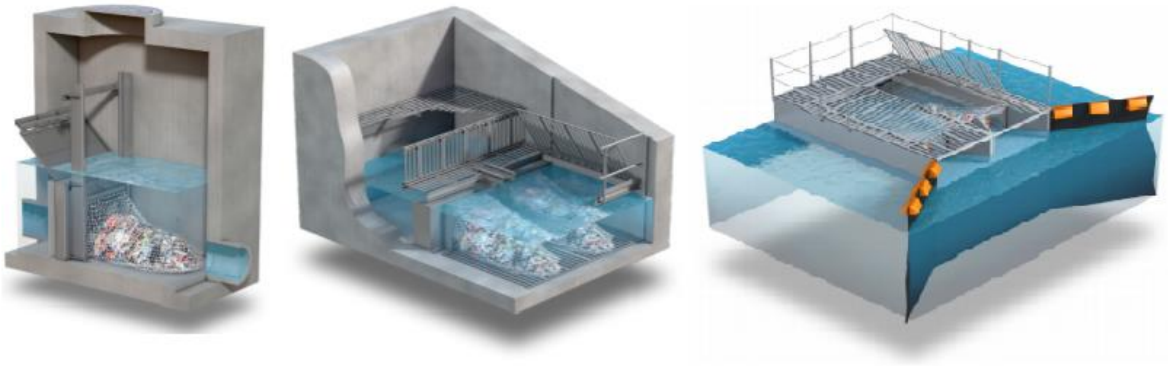

Figure 4 From left to right the inline, end-of-pipe and floating module (StormTrap, 2020a)

The company behind Trashtrap, StormTrap, has 25 years of experience in manufacturing, installing and maintaining netting systems. The TrashTrap technology has reached readiness level since it is already operating in several places in the US and for several years. According to TrashTrap, their trash netting system has a removal efficiency of 97%. Although this number is not further explained on their website, it only says that it is recorded by U.S. EPA sponsored projects. The TrashTrap systems are specially designed for stormwater, urban runoff and combined sewer overflow discharges. In other words, this method is used at the beginning of the river pathways, like stormwaters, wastewater and sewage run-offs, which later end up in/reach the main river pathway (StormTrap, 2020a).

This technology is mainly focused on catching macro plastic in a certain size range, since the mesh net size can vary between 5mm and 1 inch (25.4mm), with configurations. In addition, for standard sizes, this technology has a capacity of 25 to 50 cubic feet per net. This equals approximately a volume of 0.71m^3 to 1.42m^3 per net (StormTrap, 2020b).

Unfortunately, no explanation of the environmental impacts could be found on their website or in any other documents or articles. One of the strengths of this technology is, that it uses the passive energy of the water flow to move the litter into the nets, therefore no electricity is needed. Another strength is that the technology modules can be retrofitted in almost any stormwater system. One of the weaknesses of this technology is that the change of nets from time to time is needed. Another weakness is that only macro litter is caught, micro litter is not being caught.

When it comes to the costs of this system, there is not any information available. However, in StormTrap's brochure (StormTrap, 2020b) it is mentioned that the TrashTrap "has low capital and installation costs". Although this phrase is not further explained with any examples of fixed cost numbers or even cost estimates of the technology in general.

4.2 Interceptor

The Interceptor by the Ocean Cleanup is a litter removal solution that removes litter from rivers and therefore prevents riverine litter from entering the ocean. The purpose of the Ocean Cleanup by using the Interceptor is to tackle plastic in the 1000 most polluting rivers in 5 years. The technology consists of a floating barrier (if needed two) and a conveyor belt system. The barrier is situated in the width of the river and due to the natural current in the river, the litter will float into the barrier where it will concentrate and be directed to the conveyor belt. Because of the catamaran design of the Interceptor, the flow path is not interrupted and the litter flows easily on the conveyor belt and the water can continue its natural current. After the litter has reached the conveyor belt lifted out of the water it will be lifted higher on the belt where the waste will be and is transported to an automated shuttle which distributes the litter over one of the six waste containers. These six containers are positioned on a separate barge, which will be exchanged when all of the containers are full. The litter will then be transported and treated by the local waste management operators (The Ocean Cleanup, 2021b).

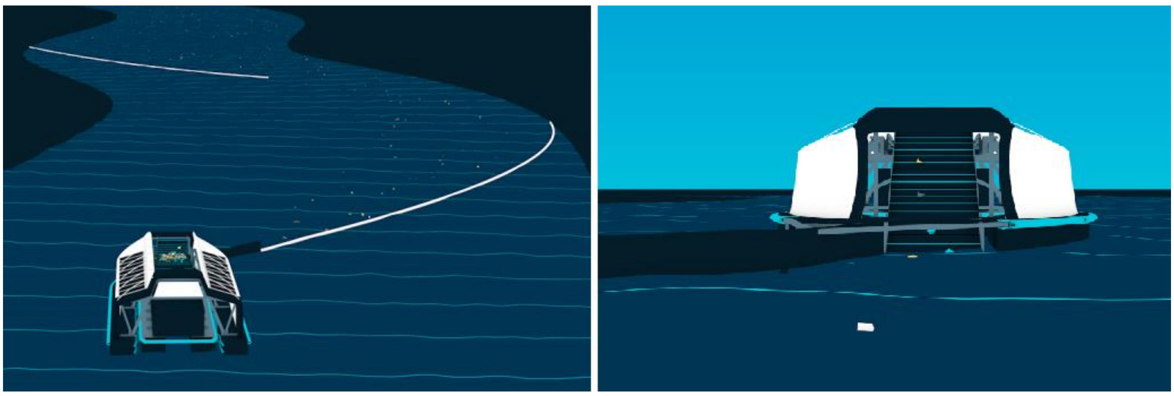

Figure 5 The Interceptor with barriers and the conveyor belt (The Ocean Cleanup, 2021b)

The technology has left the testing phase and is ready to be used in the real working environment. In 2016, the prototype and first-generation Interceptor was deployed in Indonesia and the latest Interceptor was deployed in 2020 in the Dominican Republic. At the moment there are three Interceptors operative and in use in different rivers in 'Dominican Republic, Malaysia and Indonesia' (Helinski, Poor and Wolfand, 2021).

One Interceptor has a waste capacity of 50 m^3 which is divided over the six waste containers. Under the optimal circumstance, the Interceptor can reach a removal capacity of 50 tonne of plastic per day. The Interceptor works automatically until the waste containers are full, then those need to be emptied by the local waste operators. Unfortunately, The Ocean Cleanup does not give a removal efficiency number in percentages for the Interceptor (The Ocean Cleanup, 2021b).

Interceptors are scalable and can be designed to be used in most of the world's worst polluted rivers. However, the best place for the installation of the Interceptor in the river is determined on a case-by-case basis. This depends for example on the width of the river, the flow velocity in the river, traffic, the appearance of a concentrated plastic flow in the river and the proximity to a delta. The technology is mainly designed and focused on floating riverine (plastic) macro litter (The Ocean Cleanup, 2021b).

According to the results from the environmental impact assessments done for The Ocean Cleanup, the negative impacts of the Interceptor on the environment are negligible (The Ocean Cleanup, 2021a). In addition, according to a press release by the Ocean Cleanup the floating barrier of the Interceptor does not hinder the movement of wildlife, nor does it harm the safety of wildlife (The Ocean Cleanup, 2019b).

One of the strengths of this technology is, that it is operational 24/7. Another strength is that it doesn't need the interaction of people, it works autonomously. Furthermore, it is running on renewable energy. One of the weaknesses is that it will mostly collect only floating litter, not litter that is floating in the water column nor litter that's located on the riverbed. Another weakness is that the local waste operators must be able to remove the six large waste containers (Helinski, Poor and Wolfand, 2021).

According to Helinski et al. (Helinski, Poor and Wolfand, 2021), the capital costs of an Interceptor are 780,000 U.S. dollars. This complies with the information given by the Ocean Cleanup (The Ocean Cleanup, 2019a) which says that one Interceptor costs around 700.000 euros, which equals approximately 770,000 U.S. Dollars. Besides this, there is not much information available regarding the costs of an Interceptor.

4.3 Blue Barriers

The Blue Barriers are a technology that stops plastics from reaching the oceans and it is developed by SEADS. The technology of a river boom is simple, there are two floating booms, the blue barriers, across the river which redirect all the plastic litter from the river stream. The barriers are placed strategically in a way that is most effective in collecting litter. The booms redirect the litter into a collection basin, where the litter will be taken away and sorted to be properly recycled. The blue barriers are designed in such a way that they do not interfere with the traffic in the rivers. The blue barriers are possible to be installed at the necessary distance from each other, in doing so vessels are still able to pass the barriers with just a small variation in direction. The barriers consist of two parts, a floating module and an internal steel structure which makes the barrier rigid and resistible against challenging river conditions. To optimise the collection, the barriers reach 70 to 90 cm at the water surface level. Due to that not only plastic litter floating on the water surface is collected, but also plastic litter that is floating a bit under the water surface (Ubuntoo Solutions, 2021).

Figure 6 The blue barriers by SEADS placed in a river (Ubuntoo Solutions, 2021)

The development stage in which this technology currently is is according to Winterstetter et al. (Winterstetter *et al.*, 2021) at technology readiness level (TRL) 6&7, which means it is at the pilot stage. During pilot testing, there have been done several tests in a laboratory setup and also in the natural riverine environment. At the moment work is in progress and SEADS is working to get permanent installations deployed in several rivers worldwide (SEADS, 2020).

The blue barriers can be used anywhere in a small to large river wherever litter causes a problem. This technology is mainly focused on floating macro litter. SEADS claims that the blue barriers have a removal efficiency of nearly 100% of macro litter in normal conditions and 92% in flooding conditions. Even though now the blue barriers can only catch macro litter, at the moment tests are going on to see if the blue barriers in combination with bubble curtains could be a solution to also catch microplastics from the river (SEADS, 2019a).

The costs of the Blue barriers differs according to the size of the river where the system will be deployed. According to SEADS (SEADS, 2020), the capital costs will be 220k€, 350€k, 575k€ and 950k€ for respectively a river with a size of 100 m, 200 m, 500 m and 1 km. These capital costs of the Blue barriers do not include the costs of the collection basin, where the collected waste is sorted and removed.

When it comes to environmental impact and concerns, the barrier installation has only an effect on the surface part of the river water column. Although it is mentioned that the blue barriers will not affect fish and other riverine fauna. It will be able for fish to carry on with their transit by going underneath and/or between the blue barriers (SEADS, 2019b).

One of the strengths of the blue barriers technology is, that it does not require a lot of maintenance. Another strength is that it does not need electric power to operate. One of the weaknesses is that it only captures floating macro litter on the water surface and litter in the water column.

4.4 Seabin

The Seabin is a floating litter bin in the water skimming the water surface. The purpose of the Seabin is to collect litter that is floating on the water surface in marinas, canals and harbours, preventing it from reaching the seas and oceans. The Seabin is a waste collection bin connected to a frame with a pump on it. The pump gets its energy from a power supply located nearby. Inside the bin is a reusable catch bag. The top of the bin is located just under the water surface, so the water flows into the bin. The waste that is floating on top of the water is falling into the bin and is caught by the catch bag. From underneath the bin, water is pumped out into the water body again. The Seabin is moving along with the tide in such a way that it is always able to collect litter. The Seabin should be attached to a floating dock and placed at a strategic position, in that way the tide, current and wind makes the litter reach the Seabin so that the Seabin works at the optimum performance (Seabin Project, 2021).

When it comes to the development phase of solution the Seabin technology has reached maturity level. There are currently already 860 Seabins in use in many marinas and ports all over the world. The capacity of a Seabin is 0.125 m^3 and the catch bag can hold up to 20 kg before it needs to be emptied. When looking at the removal capacity of the Seabin, one Seabin can remove approximately 1.4 tonne of waste in one year or, in other words, 3.9 kilograms per pay. Of course, this depends on the weather conditions and the volume of the litter. In addition, the catch bag has to be emptied and replaced every time it is full. Unfortunately, there is no information available on the removal efficiency of one Seabin, only the removal performance is given (Helinski, Poor and Wolfand, 2021).

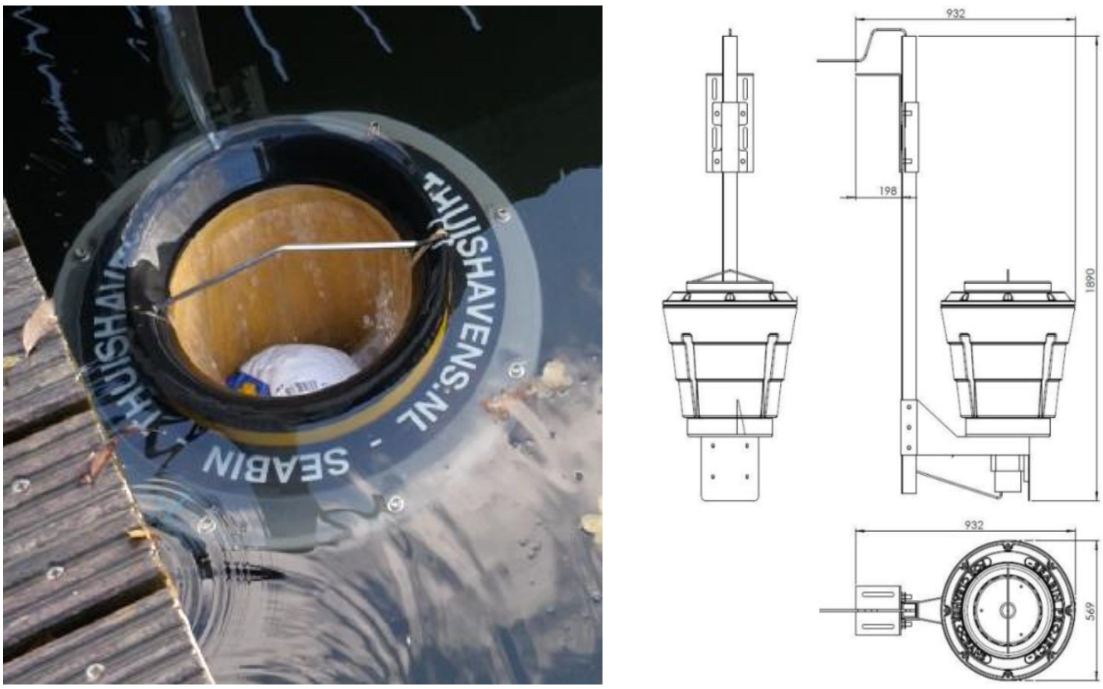

Figure 7 Example of a Seabin in a harbour and the technical specifications of the Seabin (Seabin Project, 2021)

The Seabin is designed for installation in marinas, ports and other calm water environments with a power supply available nearby. Although a certain water depth at the lowest tide of minimally 1.2m is needed for the Seabin to able to be implemented. The Seabin is useable for floating litter, it can collect macro litter and micro plastics down to 2 mm. Although it is not possible to collect large macro litter items, since those will not fit into the Seabin (Seabin Project, 2017).

Unfortunately, the environmental impacts of this invention are not being discussed on the company's website or mentioned in any other articles. One of the strengths of this technology is, that it is a small device and it doesn't take much space when in use. Another strength is, that it can catch macro litter as well as micro litter up to 2mm. One of the weaknesses of this technology is that larger polluted areas need more than one Seabin. Another weakness is that this technology only operates well in calm water areas. The next weakness is that the Seabin needs daily maintenance. It is advised that the Seabin is checked twice a day and is emptied whenever the bin is full. Furthermore, the Seabin should be checked regularly and cleaned no less than once per month (Helinski, Poor and Wolfand, 2021).

According to Helinski et al. (Helinski, Poor and Wolfand, 2021), the capital costs of the Seabin are 5820 U.S. dollars for floating docks and 7725 U.S. dollars for fixed docks. This equals approximately 4970€ for floating docks and 6600€ for fixed docks. It should be noted that the shipping costs are included in the total capital costs.

4.5 The Bubble Barrier

The Bubble Barrier is a riverine plastic removal solution by the start-up The Great Bubble Barrier. The purpose of this technology is to catch plastic litter before it reaches the seas and oceans. The Bubble Barrier works as follows, a perforated tube is lying on the bottom of the river or canal. Compressed ambient air from the tube creates a bubble curtain which is a continuous upwards current. This current is directing the plastic waste towards the water surface. The Bubble Barrier is placed diagonally in a river or a canal, because of that the natural water flow will push the plastic waste towards the side of the river where it enters into the catchment system. The catchment system will collect and retain the plastic waste and from there it will be taken out from the water for further processing. The Bubble Barrier works 24/7 and uses, wherever possible, renewable energy (The Great Bubble Barrier, 2021b).

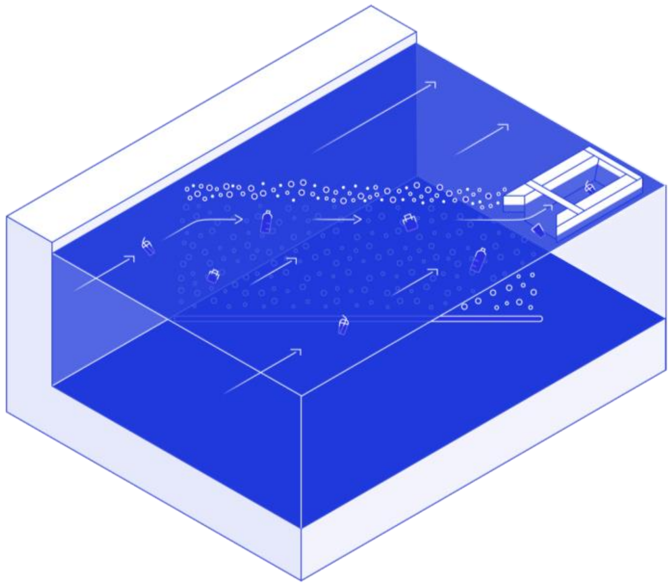

Figure 8 The Bubble Barrier (The Great Bubble Barrier, 2021b)

When looking at the development stage of this technology, the Bubble Barrier is according to Winterstetter et al. (Winterstetter *et al.*, 2021) at the moment at TRL 8. This means it is at the scale-up phase, in other words, it is in the transition from the pilot phase to the market phase. The Bubble barrier has undergone the pilot phase testing and at the moment there are already several in use in several rivers. Although there is still an improvement in progress to try to catch even smaller microplastics, with a size between 20 micrometres to 500 micrometres. When it comes to removal efficiency, according to results of pilot testing, it is calculated that the Bubble Barrier can capture around 70 to 80% of the top-surface floating plastic and 50% of underwater plastic. During testing in a river in different weather conditions it has been conducted that the Bubble Barrier caught 86% of the floating test material. The Bubble Barrier is focused on catching micro and macro litter since it can catch plastic with a size of 1 mm and bigger (The Great Bubble Barrier, 2021a).

There is not much information available on the costs of a Bubble Barrier. Although Helinski et al. (Helinski, Poor and Wolfand, 2021) categorise the Bubble Barrier as a ‘low’ costs technology, which means that the capital costs of one device are lower than approximately 8500€. However, this is not further backed up by any number or other information concerning costs. And since the Bubble Barrier needs a compressor to make the bubble curtain this number seems too low to be true. The only other information available regarding the costs of the Bubble Barrier is that the installation costs of the first Bubble Barrier at Amsterdam's Westerdok were approximately 100,000€ (Das, 2020). This number seems to be giving a more reliable view of what the costs of a Bubble Barrier can be. Of course, the costs of the technology depend on the size and the place of implementation.

When looking at environmental impact and concerns, most species are able or need a little more time to pass through the bubble barrier, furthermore fish can pass through the system's fish passage. Such a fish passage is implemented in each design and can be situated for example under the catchment system (The Great Bubble Barrier, 2021b).

One of the strengths of this technology is that it can catch small amounts of waste up to 1 mm small and the technology works for macro both micro litter. Another strength is that ships can pass the bubble barrier without any hindrance. Furthermore submerged litter is reaching the water surface. One of the weaknesses of this technology is that it is most effective for plastic litter, other litter items like metal not so much and also plastic litter that sinks to the bottom and rolls on the ground is not taken by the Bubble Barrier. Another weakness is that it may not be the best option for rivers with changing conditions. Furthermore, a careful balance is needed to create the right size of bubbles (Helinski, Poor and Wolfand, 2021).

4.6 Comparison of the removal technologies

In *Table 5* and *Table 6* the removal technologies, which are mentioned in the subchapters above, are compared with the following categories: application, maturity, litter type, efficiency, capacity and costs.

The category 'Application' shows where the technology can be applied in the river pathway for its best use. For the compared technologies the different applications are the (main) river, canals, stormwaters, wastewaters, harbours and marinas.

The category 'Maturity' describes in which phase of development the technology is at the moment. For example, if the technology is in the design phase, the pilot testing phase or if it is in the use phase. For all the technologies shown in *Table 5*, they are either in the pilot phase or are already in use.

The category 'Litter type' describes which litter the technology removes, macro litter, micro litter or both. Furthermore, if available, the size range in which the litter can be removed will be shown. All of the technologies shown in *Table 5* remove macro litter, whereof two of them remove both micro and macro litter.

The category 'Efficiency' describes the removal efficiency of the technology. The removal efficiencies are described in percentages and shows the percentage of litter that gets caught and removed by the device. Unfortunately, the removal efficiency is only available for three of the five technologies.

The category 'Capacity' describes the capacity of the device to store litter, this is shown in metric meters. Unfortunately, this information is only available for three of the five technologies described in *Table 6*. Another thing that can be noted, is that there is a big difference in capacity between those technologies. A relatively big capacity of $50m^3$ for the Interceptor compared to relatively small capacities of $0.125m^3$ and $0.71m^3$ - $1.42m^3$ (per net) for respectively the Seabin and TrashTrap. In addition, for two technologies the removal capacities will be shown as well in *Table 6*. The removal capacities describe the capacity of litter that can be removed in a day and are shown in kilograms per day.

The category 'Costs' describes the estimated capital costs for the technologies. It is hard to give a precise number of the costs for each technology because it depends on the available information on the costs. This can be hard to get since the costs can differ for each situation the technology is used in. Furthermore, some technologies have operational and maintenance costs which are difficult to determine as well without any knowledge about the circumstance in which the technology will be used. Therefore, the operational and maintenance costs are not included in this costs part. In *Table 6* below the capital costs will be categorized as followed, 'low', 'medium' or 'high'. Where 'low' stands for capital costs lower than 8500€, 'medium' stands for capital costs between 8500€ and 85000€ and 'high' stands for capital costs higher than 85000€. The way that the costs are defined is taken from Helinski et al. (Helinski, Poor and Wolfand, 2021) since for most of the technologies the costs are described in the same way as has been done in that research. Although here the costs are given in euros, compared to U.S. dollars in the research of Helinski et al. (Helinski, Poor and Wolfand, 2021). If available, besides the category 'low', 'medium' or 'high', the costs will be shown in a round number or a range of costs.

Table 5 Comparison of the removal technologies

Technology	Application	Maturity	Litter type
TrashTrap	Stormwaters and wastewaters	In use	Macro litter in size range of 5mm to 25.4mm
Interceptor	Rivers	In use	Macro litter
Blue Barriers	Rivers	Pilot testing phase	Macro litter
Seabin	Harbours and marinas	In use	Macro and micro litter (down to 2 mm)
The Bubble Barrier	Rivers and canals	In use	Macro and micro litter (down to 1 mm)

Table 6 Continuation of comparison of the removal technologies

Technology	Efficiency	Capacity	Costs (Specific costs)
TrashTrap	Efficiency of 97%	0.71m^3 to 1.42 m^3 per net**	NA*
Interceptor	NA	Capacity of 50 m^3** Removal capacity of 50000 kg/day	High, around 700.000€ (14€/(kg/day))
Blue Barriers	Efficiency of close to 100% in normal conditions and 92% in flooding conditions	NA	Medium/high, between 220.000€ and 950.000€
Seabin	NA	Capacity of 0.125 m^3** Removal capacity of 3.9 kg/day	Low, between 4970€ and 6600€ (1274 – 1692€/(kg/day))
The Bubble Barrier	Approx. efficiency of 70 to 80% for top-surface floating plastic and 50% for underwater plastic	NA	100.000€

*NA, the information on this category is not available or could not be found for that certain technology

**It has to be noted that the nets or waste bins of the devices have to be cleared and emptied when full to be able to work as efficiently as possible

Figure 9 is a scheme where the river pathway is shown with possible locations for the removal technologies compared above. Number 1 in *Figure 9* stands for the location for the Bubble Barrier since it works the best in canals and/or small rivers which can be found in the city. Number 2 stands for the location for the Blue Barriers since these operate best in rivers nevertheless the size. Which in this case is the river which enters the inhabited area from outside. Number 3 stands for the Trashtrap technology since its use is for waste and stormwater, which in this case come from the city and the industry area. Number 4 stands for the Interceptor since it can be best used in a relatively big river or the main river. Which in this case are the main river that connects the rivers from the city and from outside the city and the effluents from the industry area. Number 5 stands for the Seabin since it operates best in harbours as that is the case in this picture.

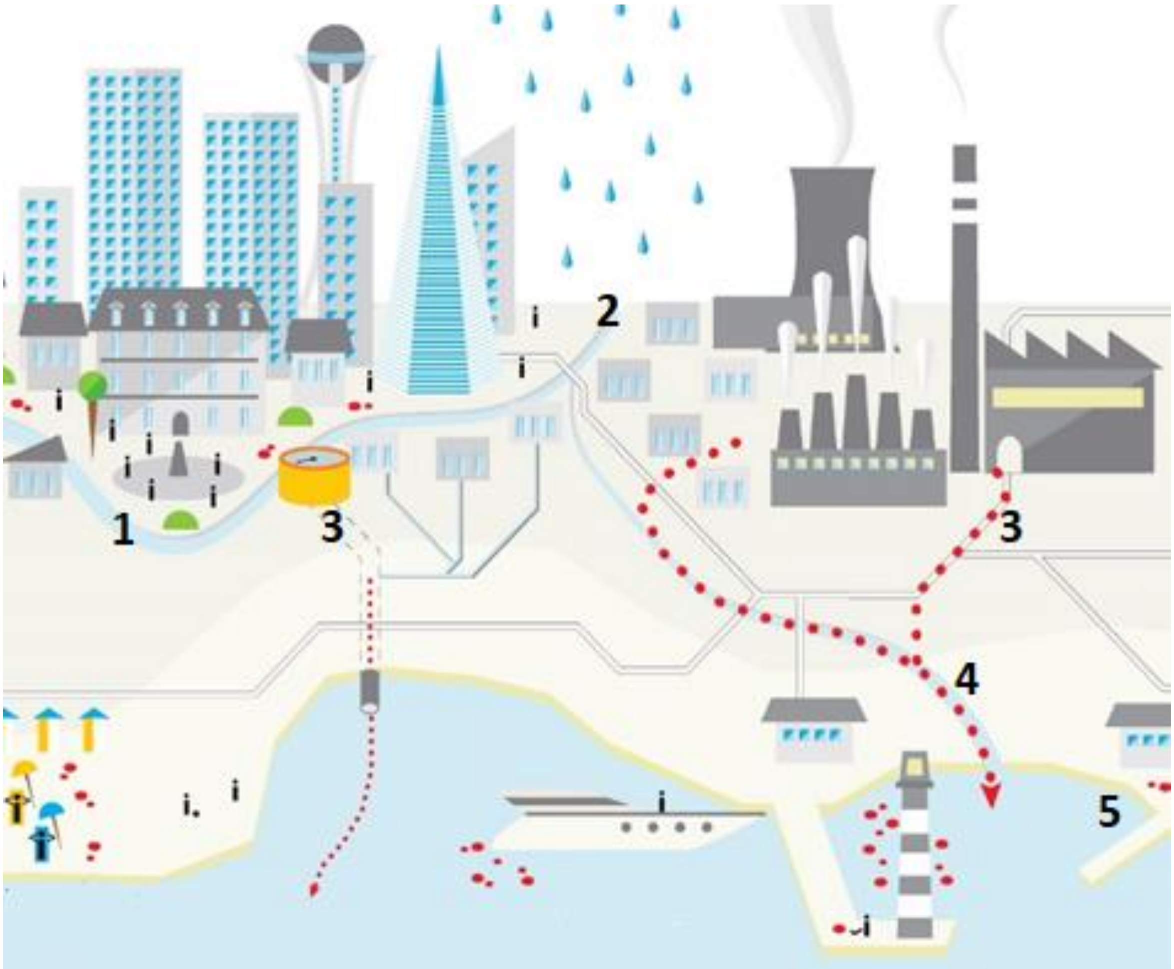

Figure 9 River pathways with possible locations for the removal technologies. The location of each technology is as follows: 1. Bubble Barrier, 2. Blue Barriers, 3. TrashTrap, 4. The Interceptor, 5. Seabin. Edited from (UNEP and GRID-Arendal, 2016).

In the best-case scenario, this setup of removal technologies shown in *Figure 9* will remove both macro litter and micro litter. With the Bubble barrier, micro litter up to 1mm can be removed from the canals in the city. Furthermore at the end of the river pathway, in the harbour, micro litter can be removed up to 2mm. Although not all the micro litter might be removed since the Seabin might not be able to catch all of it. With the Interceptor in the river before the harbour, it is even possible to prevent large macro litter items to reach the marine environment.

The estimated costs of the situation explained in *Figure 9* are approximately 1.4 million€. It should be noted that these costs do not include the costs of the Trashtraps, since these are unknown. The rest of the costs are calculated when considering, Blue barriers for a river with a size of 500m, 2 Seabins in the harbour for fixed docks and the rest of the technologies with their standard costs.

5 DISCUSSIONS

The quantity of (plastic) marine litter in the marine environment is not clear. There are not many studies that give a clear number regarding the litter that is already in or entering the marine environment. The studies that researched the amount of litter that is entering the marine environment, only give an estimate. In addition, the numbers vary a lot and do not all show results from the same research area, e.g. only coastal areas or all countries. So in the end there is not one clear number that indicates the (plastic) marine litter to the oceans and seas. In addition, all of the studies regarding the inflow of plastic into the seas and oceans, are as they say only focusing on plastic marine litter. Even though plastic is the main contributor to marine litter, all the other litter items are left aside in these studies. Also, the two lists of the 20 most polluting rivers have both different results, with a different top 20 list and with quite different yearly plastic litter input figures.

For many, if not all removal technologies, it is not clearly mentioned for what litter the technology is made. For example, it is not mentioned until what litter size the technology can remove and for what litter it is specifically built, only floating litter on the water surface or maybe as well floating litter in the water column. Most of the technologies for the removal of marine litter in rivers are mainly focused on the removal of litter on the water surface or in the water bed just under the water surface. Therefore all the litter that is appearing in the benthic habitats or the riverbed are not able to be caught and therefore won't be removed. Although it is unclear what the quantity of litter on the river bed is, it might be of a certain significance to tackle the marine litter problem.

The removal efficiency is of great importance when choosing a technology since it more or less defines the final amount of litter that can be removed at a certain time and place. The removal efficiencies of the mentioned technologies are not well explained. In the majority of the cases, it is only mentioned what the removal efficiency is and not explained how the efficiency has been tested or calculated. This makes the reliability of the removal efficiency for many of the technologies questionable. Furthermore, the removal efficiencies are not available for each of the technologies.

On the other hand, the same is happening when it comes to the environmental impacts of the technologies. For many of the technologies the environmental impact of the technology is not explained at all or not clearly explained. This means the environmental impacts are mostly mentioned without a proper investigation and are not properly substantiated. This unawareness of possible environmental impacts can cause harm to animals and nature which then will be conflicting with the goal of the technologies to better the environment.

When looking at the costs, the capital costs can be misleading, since they might not give a clear view of the costs per removed kilogram. This can be seen when looking at the specific costs of the Interceptor and the Seabin shown in table 6. There you can see that even though the Interceptor has much higher capital costs than the Seabin, but the specific costs of the Seabin far exceed the specific costs of the Interceptor.

Additionally, the costs are not available fully explained for quite a few of the technologies. This is a problem since the cost factor is usually one of the main decision-making points when deciding to buy a technology. In addition, the costs of the removal technologies in relation to the location of littering might be a bottleneck. Since, as can be seen from chapter 2.5 most of the littering is happening in low- and lower-middle-income countries. Therefore the local governments can see the cost factor as a limitation to implementing removal technologies.

6 CONCLUSION

Marine litter is a global problem and does not only affect the environment, but also the society and economy. Marine litter objects are made of various materials, although the main contributor of the global marine litter material composition is plastic with roughly 70%. The numbers regarding the inflow of plastic waste into the marine environment are various. For example, land-based sourced plastic waste is estimated to be between 4.2 and 12.7 million tonne per year. On the other hand, numbers regarding the plastic waste emissions from rivers vary with a minimum annual input of 0.41 million tonne per year to a maximum annual input of 4 million tonne per year. Furthermore, there is not much research available on this topic. On top of that those numbers only are estimated of plastic litter reaching the marine environment. Therefore the total number of marine litter that is entering the marine environment is unclear. In addition, there are two different lists of the top 20 most polluting rivers, which both show different order of most polluting rivers and quantity of litter coming from those rivers.

The best way to put a stop to marine litter is to apply prevention actions in combination with actions to remove marine litter. There are several prevention possibilities available to reduce or even terminate marine litter. These can range from improving the waste management to raising awareness, and education and behaviour change to putting in charge bans and economic incentives, changing the product design and implementing circular economy and using LCA and last but not least more innovation and research on for example improving legislations and product’s design.

On the other hand, there are several possibilities to remove litter from rivers. These technologies can be implemented in several parts of the river pathway. For example, a mesh net waste trap in wastewaters upstream from the river, a floating waste filtering trash bin in marinas or harbours, litter collecting booms in rivers, a barrier and conveyor removing litter in rivers, or a bubble curtain barrier collecting litter in rivers and canals.

Most of the removal technologies are primarily focused on the removal of macro litter. Besides that, some technologies are focused on both macro and micro litter. Furthermore, the majority of the removal technologies are mainly designed and implemented for the removal of plastic litter, other marine litter materials are usually not the main focus point.

The reason that most of the technologies are focusing on plastic litter can be traced back to the fact that marine litter consists roughly about 70% of plastic. Additionally, most of the removal technologies are designed to collect mainly litter that is floating on the water surface or litter that is floating in the water column right under the water surface.

Overall there is information available about the technologies, but when looking for more detailed information, it is hard or most of the time not possible to find. For instance, the removal efficiency of the technology is given, but there is no further explanation on how the removal efficiency has been calculated. The same accounts for information regarding the environmental impacts of the removal technologies.

Even though all those removal technologies are great inventions to tackle the (plastic) marine litter problem, the removal does not come close to the yearly input of litter to the marine environment. Therefore more of these removal technologies need to be implemented and continuously improving the technology is needed to have an optimized removal efficiency and thus best results. As well as innovation and research are needed to come up with better and new technologies regarding removal of litter, which will help to reach the point of clean rivers. In addition, the possibilities of prevention mentioned before need to be put in charge to close the tap of (plastic) litter entering the environment.

As a final note, in both prevention possibilities and removal technologies more research is needed, as well as more research about the marine litter problem itself to map the extent of the problem and to define better solutions to tackle this problem.

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