



Two years of daily monitoring of floating macro-litter at the River-Sea interface: Aarhus River, Denmark

Mirco Haseler^{a,*}, Geraldo Mihut^b

^a Coastal Sea Geography Working Group, Leibniz-Institute for Baltic Sea Research, Seestrasse 15, D-18119, Rostock-Warnemünde, Germany

^b Fondation Plast Center Danmark facilitator of the Innovation Network Danish Materials Network (DMN), Niels Bohrs Vej 6, 6700, Esbjerg, Denmark

ARTICLE INFO

Keywords:

Riverine litter
SeaProtectorOne
Single-use plastics
Baltic sea
Freshwater

ABSTRACT

Marine litter is a global problem, with rivers acting as major pathways for land-based waste entering the oceans. Current estimates of riverine litter inputs in the EU often rely on short-term visual surveys from bridges or piers, which provide incomplete data and a coarse classification of litter types. This study presents, for the first time in Denmark and the wider Baltic region, high-resolution daily (24 h) monitoring of floating macro-litter in the Aarhus River using the SeaProtectorOne device that spans the entire river width. Litter was collected continuously over two one-year periods (2021/22 and 2024/25), enabling a detailed analysis of litter dynamics at the river–sea interface. A total of 63,035 litter pieces were collected in the first year and 18,725 in the second. On average across both years, plastics were consistently dominant, accounting for 60 % of all items, followed by paper and cardboard at 23 %. Single-use plastics (53 %) together with takeaway-related paper items such as bags, food wrappers, and trays made up the majority of inputs. Pollution peaked during weekends, particularly in summer and autumn, highlighting the influence of social and recreational activities in the city center on litter generation. The results demonstrate that continuous collection provides more accurate estimates of riverine litter fluxes than visual surveys and allows detailed identification of litter types, which can inform targeted prevention and reduction measures at local and regional scales. The marked decline in litter between the two periods likely reflects the effects of local prevention measures and increased public awareness.

1. Introduction

Marine litter is defined as any waste, discarded or lost material, resulting from human activities, that entered the marine environment (Cheshire et al., 2009), and it is considered one of the most significant problems of our time (Bellou et al., 2021). It is found on beaches all around the world (Addamo et al., 2017; Andriolo and Gonçalves, 2025; Haseler et al., 2025), in the deep sea (Hanke et al., 2025a, 2025b; Peng et al., 2020), on the water surface and in the water column (MSFD TSG ML, 2023). It occurs in different size classes, commonly categorized as micro-litter (< 5 mm), meso-litter (5–25 mm), and macro-litter (> 25 mm) (JRC, 2011). Marine litter is composed of diverse materials, with plastics making up the vast majority in terms of quantity (Addamo et al., 2017; Fallati et al., 2019; Reisser et al., 2013; UNEP, 2015) and weight (Andriolo et al., 2024; Andriolo and Gonçalves, 2024). It poses severe threats to marine biodiversity, endangering thousands of species through ingestion, entanglement, and other harmful interactions (Kühn et al., 2015; Law, 2017; OWOO, 2012; Panti et al., 2019). It negatively

impacts tourism, fisheries, aquaculture, and shipping operations (UNEP, 2021) with global costs on the marine economy that could reach \$229 billion by 2030 and \$731 billion by 2050 if plastic production continues as projected (McIlgorm et al., 2022). Therefore, it is crucial to quantify the amount of (plastic) litter entering the global oceans in order to implement and assess reduction strategies (Schreyers et al., 2021). Most litter entering the marine environment is originating from land based sources (Andrady, 2011; Serra-Gonçalves et al., 2019), with rivers serving as a significant transport pathway. Research indicates that up to 80 % of all marine litter is carried to the ocean via rivers (Meijer et al., 2021; Schmidt et al., 2017; Schwarz et al., 2019; Winton et al., 2020). Global estimates suggest that rivers contribute between 0.41 and 4 million metric tons of plastic to the ocean annually, with the ten most polluting rivers accounting for 88–95 % of this load (Schmidt et al., 2017). Another study estimated the global riverine plastic input at 1.15–2.41 million metric tons per year, with the 20 most polluting rivers—predominantly located in Asia—responsible for about 67 % of the total (Lebreton et al., 2017). However, González-Fernández et al. (2021)

* Corresponding author.

E-mail addresses: mirco.haseler@io-warnemuende.de (M. Haseler), gm@plastcenter.dk (G. Mihut).

<https://doi.org/10.1016/j.marpolbul.2025.118913>

Received 5 October 2025; Received in revised form 22 October 2025; Accepted 27 October 2025

Available online 31 October 2025

0025-326X/© 2025 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

highlight that these studies are based primarily on datasets of micro-litter and meso-litter. As a result, they likely underestimated the true amount of plastic entering the sea via rivers by largely overlooking macro-litter. In contrast, a study focusing solely on macro-plastics estimated that more than 1000 rivers contribute 80 % of global riverine plastic emissions, with annual inputs ranging from 0.8 to 2.7 million metric tons, and identified small urban rivers as particularly significant sources of pollution (Meijer et al., 2021). Interestingly, while Meijer et al. (2021) focused exclusively on macro-plastics, their estimated emissions are not substantially higher than those of Lebreton et al. (2017) and Schmidt et al. (2017). For Europe specifically, rivers are estimated to transport between 1656 and 4997 metric tons of macro-litter (>25 mm) into the ocean each year, with plastics comprising over 80 % of this total (González-Fernández et al., 2021). Yet, emission estimates remain highly uncertain due to factors such as the neglect of litter retention within rivers (Schernewski et al., 2024; Schernewski et al., 2020), variations in modelling approaches (van Emmerik et al., 2018), and a general shortage of long-term field measurements (González-Fernández and Hanke, 2017). Existing measurements of floating macro-litter in Europe are largely based on short visual surveys from bridges, which, while useful, provide only limited insights (González-Fernández and Hanke, 2017). To advance understanding of litter transport into marine environments, additional field surveys and larger, long-term datasets are urgently needed (González-Fernández et al., 2021; Schreyers et al., 2021). Beyond visual observation, the

physical collection of litter is important because it enables much more detailed identification of individual litter items, their material composition, and potential sources. Given that significant knowledge gaps remain regarding litter retention and the transport of different litter types (Newbould et al., 2022), field surveys should be conducted as close as possible to river mouths. Only at this point can the most reliable estimates of floating macro-litter entering the sea be obtained, where uncertainty is lowest and representativeness highest — making such surveys a critical requirement for robust monitoring. This study provides a two-year, high-resolution analysis of floating macro-litter pollution at the outlet of the Aarhus River, using daily monitoring by an automated device that spans the entire width of the stream. Unlike short-term visual surveys, this approach delivers continuous and detailed data, offering unique insights into litter dynamics at the river–sea interface. The objectives are (i) to quantify pollution loads, (ii) to classify items in detail according to the EU Joint List of Litter, and (iii) to analyze temporal variations in litter occurrence across days, weeks, and seasons.

2. Material & method

The Aarhus River, located in eastern Jutland, Denmark, is 42 km long and drains a 324 km² basin (Fig. 1). It originates from Solbjerg Lake, southwest of Aarhus, and flows predominantly through a rural landscape of farmland, lakes, and wooded areas (Riegels et al., 2020). Along its course, the river passes through Aarslev Engso and Brabrand Lake before continuing eastward into the city of Aarhus and discharging into Aarhus Bay.

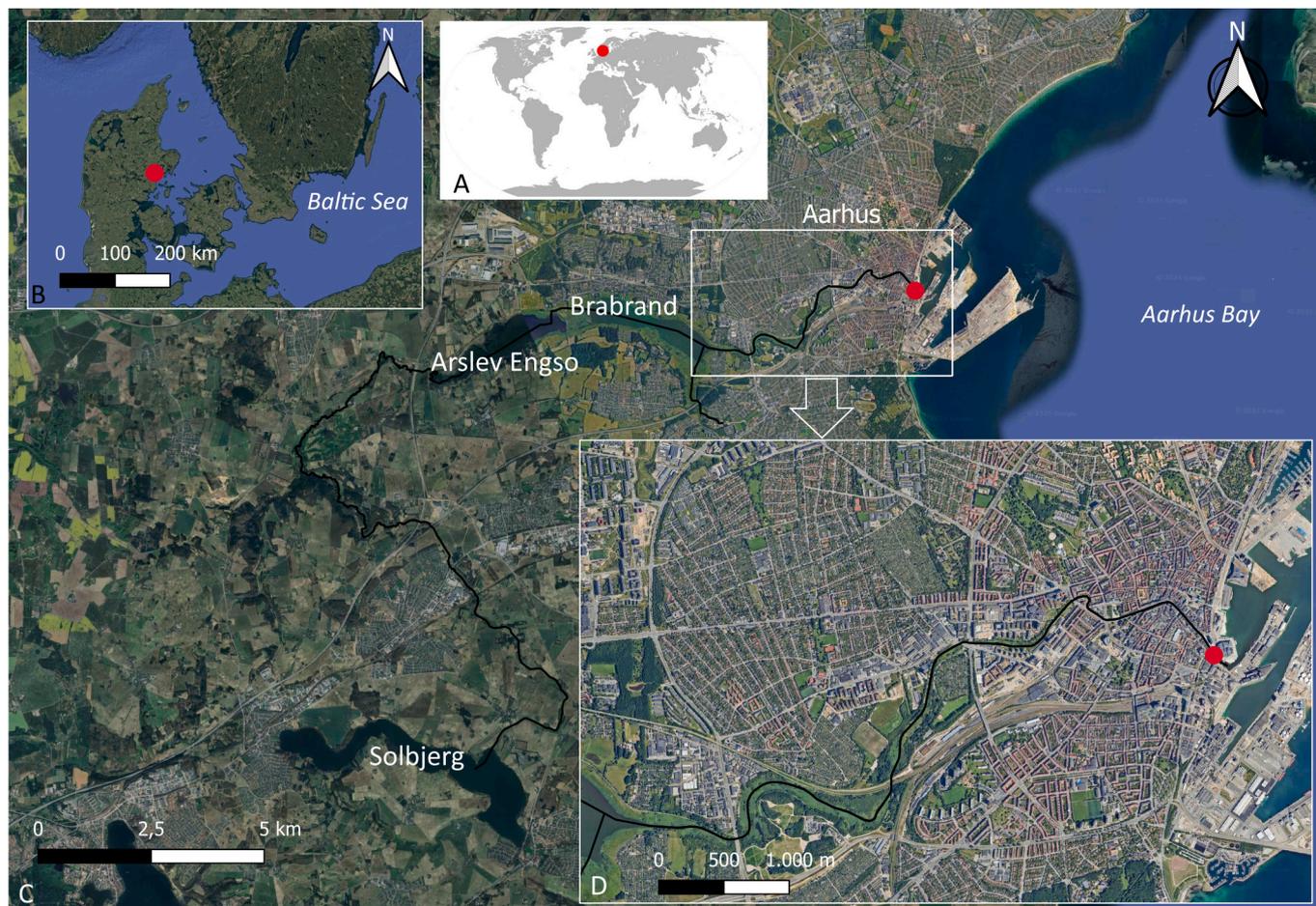


Fig. 1. (A) Denmark's location on a world map. (B) Position of the Aarhus River within Denmark. (C) The location and course of the Aarhus River (black line) in eastern Jutland, Denmark. It originates from Solbjerg Lake, flowing through Aarslev Engso Lake and Brabrand Lake before continuing eastward into the city of Aarhus and discharging into Aarhus Bay. (D) The bottom map shows the rivers course through the urban area of Aarhus. Red dots in map C and D indicate the location of the SeaProtectorOne (SPO) around 100 m before the river mouth. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

before entering the city of Aarhus (Olsen, 2002). Within the urban area, the river's final 6 km run through an artificial channel averaging about 10 m in width, with water depths ranging from 0.1 to 1.1 m and an average flow velocity of approximately 0.2 m/s (Aarhus Kommune, 2025). The river ultimately empties into the city's harbor in Aarhus Bay, an embayment of the Kattegat. Aarhus has a temperate maritime climate, with mild winters averaging around 0 °C and cool summers reaching about 20 °C. Rainfall is fairly evenly distributed throughout the year, though precipitation peaks in autumn and winter (ClimeChart, 2024). The average wind direction is westerly, with speeds typically ranging between 10 and 20 km/h (meteoblue, 2025).

Aarhus is Denmark's second-largest city, with an urban population of approximately 296,000 (Danmark Statistik, 2024). In its eastern section, the river is lined with cafés, restaurants, shops, bars, parks, and nightlife venues. Serving as a natural divider between the city's northern and southern districts, the riverfront is a popular destination for both residents and visitors, making it a central hub for social and recreational activity.

The SeaProtectorOne (SPO) device has been installed near the river's mouth at coordinates 56°09'11.3" N, 10°12'46.0" E, approximately 100 m upstream of the point at which the river enters the wider harbor basin. This location ensures the device captures floating macro-litter from the entire channel immediately before discharge into Aarhus Bay, thereby ensuring reliable measurements of river-to-sea litter transport.

The SPO is a device designed to collect floating macro-litter from rivers, channels, and streams (Fig. 2). Installed on the northern riverbank, it features a tower that lowers a boom equipped with a conveyor belt and filtration unit into the water. This filtration unit skims the surface layer (to a depth of around 30 cm). The SPO with a 35 × 60 mm grid covers 9.5 m of the 10 m wide river. To prevent litter escaping through the uncovered 0.5 m section on the southern side of the river, a guide arm (small metal groyne) was installed to direct the litter toward the center of the river. The 0.5 m opening had to remain free for operational reasons. The SPO adapts to water levels, automatically. Once a certain amount of litter or other material has been collected on the boom, it moves upwards out of the water and the material is transported by the conveyor belt into a litter container. The boom is then lowered back into the water. Sensors detect when the container is full, triggering manual emptying. Additional sensors detect ice coverage or approaching boats, automatically lifting the boom and rotating it 90° parallel to the riverbank to allow free passage. For more information on the SPO see ARTLINCO (2020).



Fig. 2. The SeaProtectorOne (SPO) in Aarhus Denmark covering 9.5 of 10 m of the channel. Red circle indicates the guidearm that lead the floating litter from the uncovered 0.5 m into direction of the SPO. The SPO features a tower that lowers a boom equipped with a conveyor belt and filtration unit (35 × 60 mm) grid into the water. This filtration unit skims the surface layer (to a depth of around 30 cm) and collects floating macro-litter. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.1. Data collection and analysis

Over a two-year period, data were collected using the SPO. During the first phase (08.03.2021–06.03.2022), daily surveys (24 h per day) were conducted over 52 weeks (364 consecutive days), with collected litter counted and analyzed each day. The analysis was based on 364 days to ensure exact comparability across full calendar weeks. This methodological choice allows a consistent evaluation at both weekly and weekday level, avoiding distortions due to incomplete weeks.

In the second phase (28.04.2024–27.04.2025), litter was collected and analyzed weekly. Due to an adjusted emptying interval, the litter container was emptied only once a week during the second year. However, litter was gathered daily (24 h per day) by SPO, with counting and categorization of the collected litter carried out only at the time of the weekly emptying.

In the first year, a separate Danish list of litter items was initially used. With the exception of a few specific items, this list was later converted to the Joint List of Litter (J-List) (Fleet et al., 2021) for comparison and harmonization. This resulted in a slight loss of detail in the data. For example, candy wrappers, chocolate bar wrappers, chocolate bar bags, and crisps bags - originally listed separately - are now grouped under "Plastic crisps packets/sweet wrappers". This type of consolidation has also been applied to several other litter items to streamline categorization and improve comparability between datasets. Other litter items made of different materials were not merged during harmonization to avoid mixing distinct litter categories. For example, pencils (wood) were placed under "Other processed wooden items 2.5 cm ≥ ≤ 50 cm" due to the absence of a dedicated litter item, while ballpoint pens (plastic) were classified as "Plastic pens and pen lids".

In the second period, the analysis followed the J-List methodology from the start, using the corresponding online photo catalogue (European Commission, 2025). For both periods the hierarchical system of the J-List was used in the highest level (5) of detail possible. For further statistical analysis of the pollution, we used 52 paired weekly observations from 2021 to 2022 and 2024–2025, matched by calendar week within the same season (Winter: weeks 1–9 & 49–52; Spring: 10–22; Summer: 23–35; Autumn: 36–48). Normality of within-pair differences was verified (Shapiro–Wilk $W = 0.979$, $p = 0.486$). We therefore applied paired *t*-tests to compare years at the seasonal level (4 strata; 13 paired weeks each). Analyses were performed in R using readxl and dplyr.

During our two study periods, the SPO operated ~98 % of the time, with only 2 % downtime, primarily for transporting collected litter to the container, maintenance, ice coverage, or boat passage. Based on 365

days, 98 % uptime corresponds to approximately 358 days of operation per year, with about 7 days of downtime.

3. Results

3.1. General results

In the first year of surveys, a total of 63,035 litter pieces, composed of 40 different litter items were collected. Plastic (60.85 %) was the dominant litter category, followed by Paper/Cardboard (22.44 %), Metal (8.93 %) and lesser amounts of other categories (Fig. 3). The top ten litter items accounted for 76.66 % of the total pollution. A list of all litter items can be found in the supplementary materials. In total 34,895 single-use plastics (SUP) pieces were collected, representing 55.36 % of all the litter.

In the second year, 18,725 pieces (across 92 litter items) were collected. Plastics remained dominant (59.05 %), paper/cardboard rose slightly (23.54 %), and metal increased to 11.20 %; other categories were comparatively minor (Fig. 3). The top ten litter items were responsible for 83.63 % of the total pollution. A total of 9425 SUP pieces were collected, representing 50.33 % of all litter, marking a 72.99 % decrease compared to 2021/22.

3.2. Seasonal litter quantities

Across all weeks, total litter collected in 2024/25 was markedly lower than in 2021/22 (mean difference = -852.1 pieces, 95 % CI [-1010.1, -694.1], $t(51) = -10.83, p < 0.001$). In 2021/22, pollution was highest in summer (21,869 pieces), followed by autumn (17,718) and winter (12,743), and lowest in spring (10,705). In 2024/25, seasonal totals were closer: spring (5621) was highest, followed by summer (4746) and winter (4646), with autumn lowest (3712). All seasons showed declines: winter -623 ($p = 0.001$), spring -391 ($p = 0.011$), summer -1317 ($p < 0.001$), and autumn -1077 ($p < 0.001$).

3.3. Top ten litter items

The clear decrease in overall litter quantities is reflected in the comparison of the top ten litter items between 2021/22 and 2024/25 (Table 1). In the first survey year, the ten most common litter items accounted for 48,323 pieces, representing 76.66 % of all litter. By the second survey year, the composition had shifted, with the top ten litter items contributing an even larger share of 83.63 % of the total, but with absolute quantities (15,659 pieces) markedly lower. While five SUP items appeared in the top ten in 2021/22, only two remained in the top ten by 2024/25, reflecting a substantial decline in SUP items overall.

The majority of the top ten litter items in 2021/22 experienced a

notable decrease in numbers, ranging from 18.28 % to 94.94 % (an average of 69.35 %) (Table 2). There was also a general decline in other litter items not among the top ten. The quantity of expanded polystyrene (EPS), including both pieces and packaging, fell by 91.66 %, from 1367 to 114 pieces. The number of plastic caps and lids from drink containers decreased by 97.05 %, from 747 to 22. Balloons and sticks for balloons dropped from 127 to 25 (decrease of 80.31 %). With the end of the COVID-19 pandemic, there was a sharp decline in the number of plastic single-use face masks, which dropped from 1231 in 2021/22 to zero in 2024/25, while single-use gloves fell from 308 to 14 (a decrease of 95.45 %).

To improve comparability and visual understanding of the figures, results are presented from January to December. Accordingly, the 2022 data (01.01.2022–06.03.2022) was placed before the 2021 data, and the 2025 data (01.01.2025–27.04.2025) before the 2024 data. This formatting ensures a clearer interpretation of seasonal patterns within a standard calendar year.

3.4. Monthly litter quantities

In the first year, monthly pollution ranged from 2792 pieces in April to a peak of 8317 in September, with an average of 5253 ± 1879 per month and a median of 5578 (Fig. 4). The months of July and August showed pollution well above the monthly mean. Relatively moderate values were displayed in January, March, and April, with all three months remaining below 3500. Litter quantities then rose steeply in summer, staying high through September before gradually declining toward the end of the year. By November and December, the monthly totals had fallen below the mean, closing the year at levels similar to those recorded in the spring months.

In the second monitoring year (2024/25), the monthly distribution was considerably lower and more balanced. Pollution totals ranged from 762 pieces in November to 2279 in March, with a yearly mean of 1560 ± 438 per month and a median of 1599 (Fig. 4). Not a single month in 2024/25 reached even the lowest monthly pollution value of the first monitoring period (2792 in April 2021/22), and all monthly values fell within a relatively narrow band. A modest increase was observed in March which represented the highest monthly value of the year. Afterward, litter counts stabilized around 1200–2000 per month, with no extreme peaks and only a slight pollution decrease in October and November.

3.5. Weekly litter quantities

The weekly litter data collected at the Aarhus River mouth (Fig. 5) show clear differences between the two monitoring periods. During 2021–2022, litter quantities displayed high variability with several

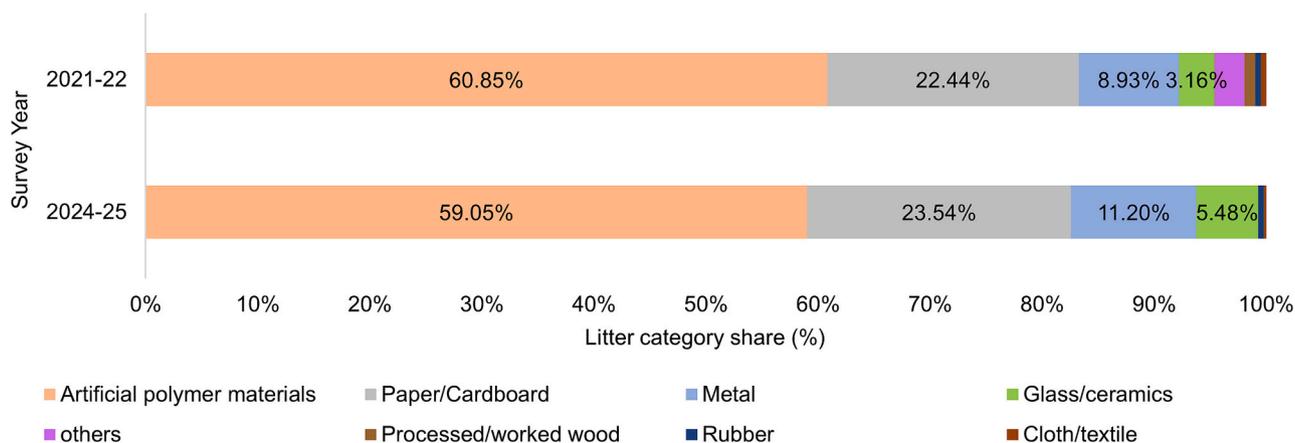


Fig. 3. Proportional composition of litter categories (%) collected with the SeaProtectorOne (SPO) in the Aarhus River in 2021/22 (top) and 2024/25 (bottom).

Table 1

Top ten litter items collected in 2021/22 (upper table) and 2024/25 (lower table) using the SeaProtectorOne (SPO). The J code and J List Type code (from the Joint List of Litter Categories) are given for each litter item. Also shown are the categories, quantities, percentages and cumulative shares (%). Single-use plastic items are labelled SUP.

	J code	J list Type Code	SUP	Litter item	Category	Quantity	%	Cumulative%
1	4	pl_nn_bag_smbg_	SUP	Small plastic bags, e.g. freezer bags incl. Pieces	Plastics	9412	14.93 %	14.93 %
2	227	pl_fc_tab_cups_hpcp_	SUP	Cups and lids of hard plastic	Plastics	9001	14.28 %	29.21 %
3	27	pl_sm_but_	SUP	Tobacco products (cigarette butts / filters) and snus	Plastics	5578	8.85 %	38.06 %
4	156	pp_nn_frg_		Paper fragments	Paper/Cardboard	5102	8.09 %	46.15 %
5	30	pl_fc_wrp_cwls_crsp_	SUP	Plastic crisps packets/sweets wrappers	Plastics	4559	7.23 %	53.39 %
6	245	pp_fc_tab_tray_		Paper food trays, food wrappers, drink containers	Paper/Cardboard	4343	6.89 %	60.28 %
7	175	me_fc_b&c_cans_bevg_		Metal drinks cans	Metal	4051	6.43 %	66.70 %
8	147	pp_nn_bag_		Paper bags	Paper/Cardboard	2210	3.51 %	70.21 %
9	231	pl_fc_tab_stst_strw_	SUP	Plastic straws	Plastics	2074	3.29 %	73.50 %
10	200	gc_nn_b&c_bott_		Glass Bottles incl. Pieces	Glass/ceramics	1993	3.16 %	76.66 %

	J code	J list Type Code	SUP	Litter item	Category	Quantity	%	Cumulative%
1	227	pl_fc_tab_cups_hpcp_	SUP	Cups and lids of hard plastic	Plastics	7356	39.28 %	39.28 %
2	175	me_fc_b&c_cans_bevg_		Metal drinks cans	Metal	1870	9.99 %	49.27 %
3	147	pp_nn_bag_		Paper bags	Paper/Cardboard	1634	8.73 %	58.00 %
4	200	gc_nn_b&c_bott_		Glass Bottles incl. Pieces	Glass/ceramics	1019	5.44 %	63.44 %
5	245	pp_fc_tab_tray_		Paper food trays, food wrappers, drink containers	Paper/Cardboard	851	4.54 %	67.98 %
6	158	pp_nn_opp_		Other paper items	Paper/Cardboard	660	3.52 %	71.51 %
7	79	pl_nn_frg_nofp_smal_		Fragments of non-foamed plastic 2.5 cm > = < = 50 cm	Plastics	625	3.34 %	74.85 %
8	4	pl_nn_bag_smbg_	SUP	Small plastic bags, e.g. freezer bags incl. Pieces	Plastics	616	3.29 %	78.14 %
9	244	pp_fc_tab_cups_		Paper cups	Paper/Cardboard	533	2.85 %	80.98 %
10	25	pl_sm_tob_		Plastic tobacco pouches / plastic cigarette packet packaging	Plastics	495	2.64 %	83.63 %

Table 2

The ten most common litter items collected with the SeaProtectorOne (SPO) from 2021/22 and their corresponding quantities in 2024/25, including the absolute and percentage decrease. Single-use plastic items were labelled with SUP.

	SUP	Litter item	Category	Quantity 2021/22	Quantity 2024/25	Decrease in numbers and in %
1	SUP	Small plastic bags, e.g. freezer bags incl. Pieces	Plastics	9412	616	8796 / -93.46 %
2	SUP	Cups and lids of hard plastic	Plastics	9001	7356	1645 / -18.28 %
3	SUP	Tobacco products (cigarette butts / filters) and snus	Plastics	5578	445	5133 / -92.02 %
4		Paper fragments	Paper/Cardboard	5102	660	4442 / -87.06 %
5	SUP	Plastic crisps packets/sweets wrappers	Plastics	4559	257	4302 / -94.36 %
6		Paper food trays, food wrappers, drink containers	Paper/Cardboard	4343	851	3492 / -80.41 %
7		Metal drinks cans	Metal	4051	1870	2181 / -53.84 %
8		Paper bags	Paper/Cardboard	2210	1634	576 / -26.06 %
9	SUP	Plastic straws	Plastics	2074	105	1969 / -94.94 %
10		Glass Bottles incl. Pieces	Glass/ceramics	1993	1019	974 / -48.87 %
Total Top 10				48,323	14,813	33,510 / -69.35 %

pronounced peaks. Pollution exceeded 1000 litter pieces in 32 weeks, with the maximum of 2436 recorded in week 26 (late June / early July). In contrast, the lowest weekly count occurred in week 51 (late December), with 330. On average, 1212 litter pieces were collected per week (median: 1223), with a standard deviation of 527, reflecting the strong variability within this first year period. The weekly pollution of SUP ranged from 47.80 % to 64.15 % and was in average 55.74 % with a standard deviation of 3.63 % (median 55.37 %).

In the 2024–2025 period, overall litter quantities were markedly lower, and the weekly variation less pronounced. The maximum weekly value was 977 litter pieces in week 36 (early September). The lowest value was recorded in week 41 (early October) with 28. For the majority of weeks (33 in total), the weekly litter counts ranged between 205 and 494. The average weekly pollution was 360 (median: 338), with a standard deviation of 193, showing a much narrower variation compared to the first period. The weekly pollution of SUP ranged from 27.63 % to 78.06 % and was in average 51.84 % with a standard deviation of 10.42 % (median 51.65 %).

3.6. Weekday pollution 2021–2022

The quantity of litter pieces collected per day ranged from 24 to 1233 (mean: 173.2 ± 160.3; median: 120.5).

The heatmap (Fig. 6) illustrates the average number of litter pieces collected per weekday across the four seasons during the 2021–2022 monitoring period. Clear seasonal differences are visible, with summer and autumn showing the highest values, while spring and winter are associated with lower levels of pollution.

Across all seasons, Fridays and Saturdays consistently stand out as the days with the highest average litter counts, reaching up to 488.5 on Saturdays in summer and 428.8 on Fridays in autumn. By contrast, Tuesdays consistently show the lowest counts, followed by Mondays and Wednesdays, which generally remain below 150. Thursdays and Sundays typically fall between these extremes, showing higher averages than most weekdays but lower than the weekend peaks observed on Fridays and Saturdays.

Yearly averages underline these patterns: Saturdays (319.9) and Fridays (296.5) recorded the highest values, while Tuesdays, Wednesdays, and Mondays were lowest. Thursdays had higher pollution than the three weekdays before, reflecting the start of increased weekend activity, while Sundays showed a decline from the weekend peak but still remained higher than early-week levels.

Overall, the results reveal strong temporal patterns in litter occurrence for both weekly cycles (weekdays vs. weekends) and seasonal dynamics (summer/autumn vs spring/winter).

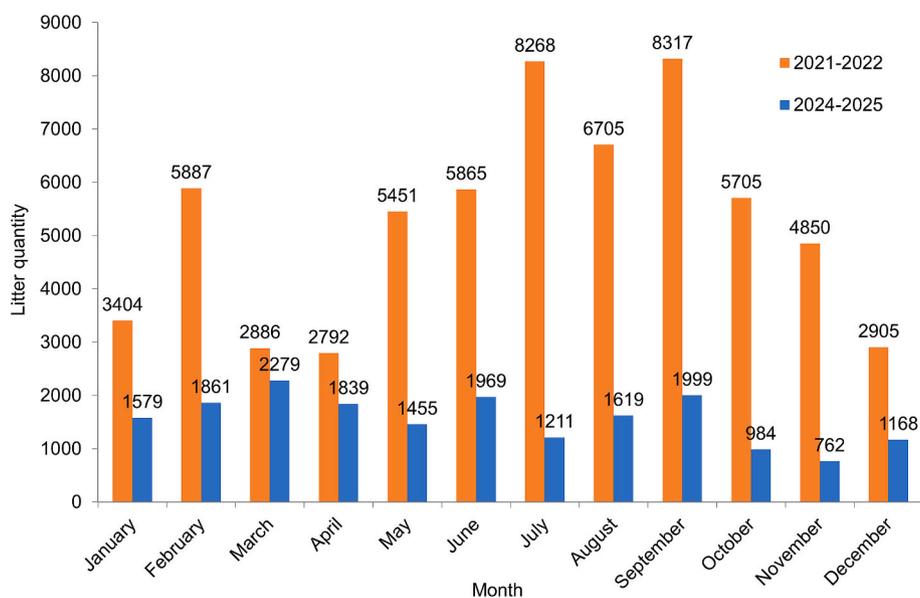


Fig. 4. Monthly litter quantities collected by the SeaProtectorOne (SPO) at the Aarhus River mouth, comparing 2021–2022 (orange) with 2024–2025 (blue). Values represent total counted litter pieces per month, illustrating strong seasonal variability in 2021–2022 and an overall decline in litter quantities between the two periods. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

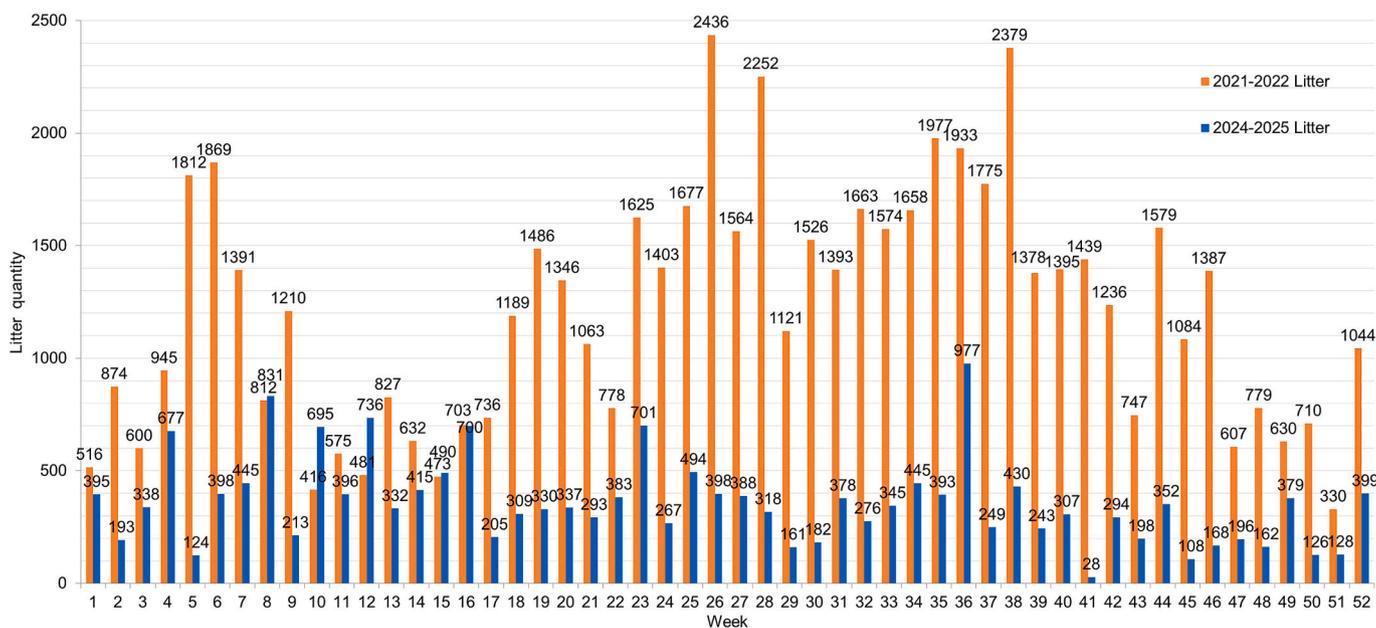


Fig. 5. Weekly quantities of litter collected by the SeaProtectorOne (SPO) at the Aarhus River mouth, comparing the periods 2021–2022 (orange) and 2024–2025 (blue). The results show seasonal variation in 2021–2022, alongside a substantial overall reduction in litter in 2024–2025, with consistently lower weekly quantities. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Discussion

The composition of litter observed in the Aarhus River differs notably from floating macro-litter reported in other European rivers. While plastics were the dominant category in both of our survey years (60.85 % in 2021/22 and 59.05 % in 2024/25), they accounted for a much lower proportion than the 81 % of plastic reported in González-Fernández, et al. (2018) or the 82 % reported by González-Fernández et al. (2021). A study of the Tiber River in Italy reported plastics as accounting for an average of 92.8 % of all floating litter (Cesarini et al., 2022), while short-term surveys using litter booms in rivers in Sweden, Estonia, and Finland found plastics to make up on average 85–95 % of all

captured items (BLASTIC, 2018).

In Aarhus, paper/cardboard (22–24 %) and metal (9–11 %) represented much larger proportions than the European averages of 9 % and 4 %, respectively reported by González-Fernández et al. (2021), Glass/ceramics (3–5 %) were also present in Aarhus, but were absent from the European datasets. The studies by González-Fernández, et al. (2018), González-Fernández et al. (2021), and (Cesarini et al., 2022) are all based on short visual observations. The largest of these, González-Fernández, et al. (2018) was conducted from bridges across 53 rivers in 15 European countries, often at locations further downstream from the main litter sources, such as urban areas. By contrast, the litter in our study was collected directly in Aarhus city center, in very close

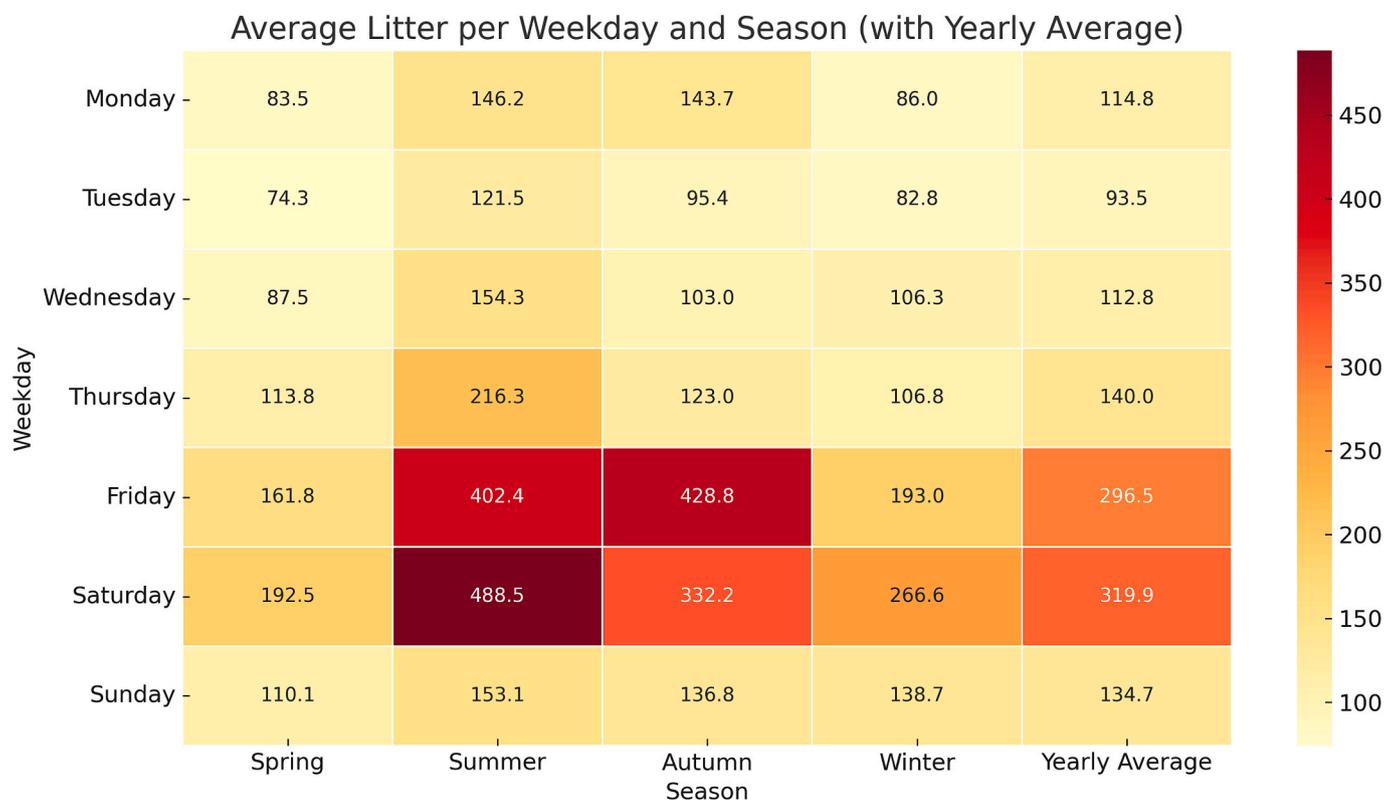


Fig. 6. Average number of litter pieces per weekday, collected with the SeaProtectorOne (SPO) in 2021/22, shown by season and for the annual mean. Each season spans 13 weeks: Spring (CW 10–22), Summer (CW 23–35), Autumn (CW 36–48), Winter (CW 49–52 & 1–9); the yearly average uses CW 1–52.

proximity to major litter sources. This likely explains the higher proportions of short-time buoyant litter like paper, metal, and glass, which most likely enter the river from the urban environment and are intercepted within very short time, before they can fragment, degrade or sink. In other studies, like the broader European study, these items may already have sunk or fragmented before reaching the observation points, resulting in lower numbers. Moreover, many of the paper litter items collected in Aarhus were relatively small in size and would likely not have been visible from a bridge, further contributing to the lower proportions of paper reported in [González-Fernández, et al. \(2018\)](#) and [Cesarini et al. \(2022\)](#).

4.1. Top litter items – comparing physical collection and visual observation

The comparison of our top litter items is made against the ‘General Top Items list’ of floating macro-litter in European rivers provided by [González-Fernández, et al. \(2018\)](#), since no Danish rivers were included in their study. In Europe, observations of floating litter were usually conducted visually from elevated points (e.g., bridges, piers, pontoons) to improve visibility ([González-Fernández and Hanke, 2017](#)). However, because no litter was physically collected, their level of identification was often limited. This is reflected in the large share of undifferentiated litter items in the European study. These include ‘plastic pieces’ (38.59 %), ‘cover/packaging’ (8.42 %), ‘polystyrene pieces’ (6.35 %), and ‘other paper items’ (4.01 %), which together account for 57.37 % of litter. In the Italian study by [Cesarini et al. \(2022\)](#), undifferentiated items such as ‘plastic and polystyrene pieces’ accounted, on average, for 61.25 % of all litter recorded. In contrast, all these litter items together represented only 12.02 % in our first survey year and 7.22 % in the second. This discrepancy is explained by the fact that our litter was physically collected, enabling far more detailed classification. Items that in a visual survey might be recorded simply as a generic “plastic piece”

or “paper item” could in our dataset be identified more precisely as small plastic bags, cups and lids, paper bags, food wrappers, or paper cups, etc. This is supported by findings from the BLASTIC project, where litter collected from various European rivers discharging into the Baltic Sea achieved a higher identification rate of around 80–90 %. Here, cigarette butts were the dominant item, accounting for 50–76 % (average 65.2 %) of all litter, followed by unidentified plastic pieces (average 10.3 %), sweet wrappers (average 9.0 %), and plastic bags (average 6.7 %) ([BLASTIC, 2018](#)).

4.2. Urban social activities as key drivers of litter input

The Aarhus River flows for its first 36 km bordered by partly dense arboreal and shrubby riparian vegetation, before passing through Aarslev Engso and Brabrand Lake and eventually entering the city of Aarhus. This combination of riparian vegetation and lakes is likely to play an important role in preventing floating macro-litter from passing through. Not only can vegetation trap floating litter within the river ([Newbould et al., 2022](#)), it can also act as a barrier, preventing litter from nearby land-based sources from reaching the water in the first place. Previous research suggests that only a relatively small share of litter present in river systems actually reaches the sea, as large amounts are stored within the river where they can remain for extended periods ranging from years to potentially centuries ([van Emmerik et al., 2022](#)). This is supported by findings from other studies, where litter transport was shown to decrease by 70–90 % along a 131 km stretch of the Meuse River ([van Emmerik et al., 2023](#)) while model simulations suggest that more than 99 % of emitted litter can be retained within estuarine systems alone ([Schernewski et al., 2024](#)).

In the Aarhus River, we assume that most of the litter intercepted by the SPO originates from the final 6 km of its course. The first 4.8 km downstream of Brabrand Lake runs through a semi-urban landscape, where the river is still bordered by vegetated buffer zones 5–70 m wide

and park-like surroundings. However, in the last 1.2 km, the river is confined to a 10 m-wide artificial channel, with dense urban infrastructure extending directly to the water's edge and no buffer zones. Here, the banks consist entirely of flat concrete walls, leaving virtually no opportunity for litter to accumulate. This area also concentrates the highest levels of human activity around the Aarhus River; a condition typically associated with elevated litter inputs (Tasseron et al., 2023; Tasseron et al., 2020; van Emmerik and Schwarz, 2020). We therefore estimate that up to 95 % of the litter originates from this final stretch of 1.2 km.

This assumption is strongly supported by the composition of the top ten litter items in both survey years and by the temporal patterns shown in the heatmap (Fig. 6). The findings suggest that most litter in the Aarhus River originates from social and recreational activities in the city center, with peaks particularly evident on weekends and during the summer months. SUP such as cigarette butts, plastic cups and lids, small plastic bags, and sweet wrappers—together with other common items like metal cans, glass bottles, and paper food trays and wrappers—are all typically associated with nightlife, restaurants, bars, and outdoor dining and drinking, which are heavily clustered along the final 1.2 km of the riverfront.

4.3. Weather and litter flux in Aarhus

In the first monitoring year, no increase in litter collection was observed after periods of heavy rainfall or strong winds, while for the second year no such analysis was done since litter was only collected weekly. This contrasts with findings from other studies, which report elevated litter flux after such events, as accumulated material is often remobilized during high wind speeds or intense rainfall (Cesarini et al., 2022; Lincoln et al., 2022; van Emmerik et al., 2022). In our case, the effect may be limited because there are few potential retention zones along the Aarhus River, within the final 1.2 km where most litter is assumed to originate. Moreover, while unfavorable weather conditions such as heavy rain or strong winds could increase remobilization of litter further upstream, the same conditions are also likely to reduce outdoor social and recreational activities in the city center. This would lower the immediate input of litter items typically found among our top ten categories, potentially offsetting any additional litter transport caused by such weather events.

4.4. Difference in the litter amount of the two years

The decrease in litter from the first to the second survey year was pronounced, with a 44,310 pieces reduction (70.3 %). Research has demonstrated that variability in the quantity of litter is a well-documented phenomenon across marine compartments. However, there is a lack of long-term data concerning floating macro-litter in rivers. Mixed trends have been observed in the literature. For instance, Kelly et al. (2023) monitored floating marine plastic litter in Nova Scotia, Canada, over a 30-year period, finding a significant increase in small plastic debris in the 2010s compared to the 1990s, while large plastic items declined over the same period. On a broader scale, EU-wide monitoring recorded a 29 % decrease in beach macro-litter between 2015/16 and 2020/21 (Hanke et al., 2025a, 2025b). On the other hand, a seven-year study of riverside pollution in Germany (2016–2022) revealed no significant alterations in litter density, composition, or sources (Dittmann et al., 2024).

The present study covers two one-year monitoring periods separated by approximately two years. As a result, it remains uncertain whether the observed 70.3 % reduction represents a long-term trend or merely natural variability, as documented in many studies worldwide. The impact of the COVID-19 pandemic on litter levels during the first survey year must also be considered. Studies show that the consumption of packaging and single-use plastics rose during the pandemic (European Environment Agency, 2025), with “on-the-go plastics” such as food

wrappers (54 %), takeaway containers (12 %), and bottles (9 %) showing the greatest increases (Winton et al., 2022). At the same time, the growth of takeaway consumption and the gradual transition away from certain single-use plastics drove an increase in paper and cardboard packaging (PPWR, 2025). This likely contributed to higher usage of paper-based items such as bags, food wrappers, and trays—items that, once discarded, tend to fragment quickly in aquatic environments, adding to the overall paper litter load. While the pandemic likely contributed to elevated litter levels in the first year, a range of other factors—regulatory, societal, and local initiatives—help to explain the sharp decrease observed in the second year.

4.5. The role of EU legislation and local initiatives in reducing litter

The EU's Directive on single-use plastics, which came into effect on July 3, 2021, included a ban on certain single-use plastic items such as cotton bud sticks, cutlery, plates, straws, stirrers, and sticks for balloons where environmentally friendly alternatives are available (EU, 2019). This legislation is likely to have had a significant impact on the presence of these SUP items. For example, plastic straws dropped by 94.9 %, while balloons and sticks for balloons declined by 80.3 %. As existing stocks of such SUP items were still permitted to be used until they were exhausted, the reduction in these items most likely occurred gradually over time.

The reduction in ‘Small plastic bags, e.g. freezer bags incl. pieces’ from 9412 to 616 can likely be attributed to a combination of factors. The end of COVID-19 restrictions may have reduced the frequency of outdoor social gatherings and takeaway consumption, lowering litter generation. At the same time, regulatory measures have significantly restricted the availability of such bags. The EU Single-Use Plastics Directive (EU, 2019), the introduction of bans (on specific bags), a mandatory charge of at least DKK 4 for carrier bags in Denmark (Ministry of the Environment and Gender Equality, 2020), and the local ban on thin plastic bags in Aarhus (Aarhus Kommune, 2019b) probably all contributed to a substantial decline in their use and subsequent littering.

The 18.3 % reduction in cups and lids of hard plastic is likely linked to the EU Single-Use Plastics Directive (EU, 2019), and the introduction of a reusable cup system launched in Aarhus in January 2024. The three-year pilot project, developed in collaboration between the Municipality of Aarhus, local restaurants and cafés, and circular economy experts, aims to demonstrate the feasibility and benefits of replacing SUP-takeaway packaging with reusable alternatives. The initiative began on January 17, 2024, with the rollout of reusable to-go cups and is planned to expand to other common types of takeaway food containers during the trial period (REUSEABLE, 2025; VisitAarhus, 2025).

The general reduction in smaller items of litter, such as small plastic bags, sweet wrappers, cigarette butts and packaging, snus, paper bags, paper food wrappers and small fragments of paper or plastic, is beside the EU Single-Use Plastics Directive (EU, 2019) also likely to be linked to Aarhus Municipality's “Small Waste – Big Problem” campaign. The campaign targeted areas with high levels of small litter, including parks as well as busy transport hubs. Measures included graphics on light rail trains, platforms and bins, posters across the city, giant cigarette butt installations and public engagement events involving the distribution of pocket ashtrays (Aarhus Kommune, 2024; Letbanen, 2024). These combined efforts together with the “Aarhus Plastics Strategy” (Aarhus Kommune, 2019b) probably raised awareness and encouraged more responsible disposal behavior. The strategy combines municipal procurement and waste sorting improvements with measures to reduce SUP at public events. It also incorporates educational initiatives for citizens and schools, as well as collaborations with companies and research institutions. These initiatives aim to prevent plastic waste at source while promoting recycling and circular economy solutions across the city.

The sharp decline in cigarette butts can be attributed not only to the “Small Waste – Big Problem” campaign (Aarhus Kommune, 2024;

Letbanen, 2024), but also to broader societal and regulatory changes. According to the Danish Research Center (HDR, 2024), the proportion of cigarette litter in the environment decreased from 62 % in 2023 to 58 % in 2024. Smoking rates have also fallen slightly, with 18 % of Danes reporting daily or occasional smoking in 2020 compared to 17 % in 2024 (SDU, 2025). Nevertheless, the use of alternative nicotine products has increased: the use of smokeless products, such as snus and nicotine pouches, rose from 4 % in 2022 to 6 % in 2024 (SDU, 2025). In Aarhus, local smoking bans introduced after the City Council's decision in December 2019 have most likely further contributed to this decline. These bans prohibited smoking in most municipal outdoor areas under the council's authority, including bus stops and other public spaces (Aarhus Kommune, 2019a; DR.DK, 2020). Although these restrictions were implemented earlier, their full impact may have only emerged gradually, contributing to the recent decline in cigarette litter. Public awareness campaigns such as 'Small Waste – Big Problem', which was first launched in 2023, explicitly targeted the disposal of cigarette butts in busy public spaces (Aarhus Kommune, 2024). Such initiatives have probably encouraged behavioral change by reminding smokers of their responsibility to dispose of litter properly. Visual reminders on trash bins, sidewalk tiles, posters and large cigarette butt installations in the city center may have reduced the number of cigarette butts entering the environment and ultimately reaching rivers.

Metal drink cans and glass bottles decreased by roughly half between the two monitoring years (–53.8 % and – 48.9 %, respectively). This decline could be likely linked to Denmark's nationwide deposit-return system for beverage containers, which achieved a return rate of 93 % in 2024 (Dansk Retur System, 2025a). Since the system has been in place for many years, it is somewhat surprising that the numbers were considerably higher in the first survey year. One possible explanation is increased outdoor consumption during the COVID-19 period, which may have led to more improper disposal. In addition, Aarhus has strengthened local incentives for correct waste management, including digital maps to locate nearby recycling stations, one-page sorting guides for materials such as glass and metal (Kredslob, 2025), and public awareness campaigns with instructional videos. The return system itself is also continuously optimized—for example, with high-capacity return stations capable of processing up to 120 bottles and cans per minute (Dansk Retur System, 2025b).

A sharp reduction was also found in expanded polystyrene (EPS) pieces (92 %) which is likely linked to EU restrictions on SUP containers and beverage cups (EU, 2019). In addition, the EPS Cycle (2025), extended to include recycling of construction EPS, with new regulations that entered into force on 1 January 2025 (Danish industry, 2025), which may have further reduced polystyrene leakage—particularly from insulation materials often cut and stored outdoors. Plastic caps/lids drinks dropped 97 % probably due to the fact that they have to remain attached to the drink containers during the products' intended use stage (EU, 2019). This is supported by the statement of the Danish Environmental Protection Agency (2025) that as many as 99 % of all plastic bottles are now returned with the lid on.

4.6. Decline in specific litter items following the end of COVID-19 restrictions

Plastic 'single-use face-mask' counts dropped by 100 %. This decline is most likely linked to the phasing-out of COVID-19 mask mandates in Denmark, with all remaining restrictions, including mask mandates, fully removed on 1 February 2022 (Public Health Ontario, 2022; The Atlantic, 2022). The same policy change likely also contributed to the decline (94.45 %) in single-use gloves, as their use in public spaces sharply decreased once pandemic-related hygiene measures were no longer in place.

4.7. Performance of the SeaProtectorOne (SPO)

Before the installation of the SPO in Aarhus, a test of the SeaProtectorOne (SPO) was conducted between 29 April and 9 July 2020 to evaluate its performance. The producer, All in On Green, collaborated with Artlinco to trial a prototype, both to assess its commercial viability and to identify potential weaknesses affecting functionality. The test was conducted in the Gudenå (Gudenåen), Denmark's longest river, which flows through central Jutland. In that experiment, grid sizes of 42 × 60 mm and 20 × 60 mm were employed. By contrast, the present study employed an intermediate grid size of 35 × 60 mm. Results published by Artlinco reported an overall recovery rate of 84 % across a variety of test objects, including bottles (100 % recovered), plastic bags (100 %), paper cups (100 %), plastic containers (93 %; one lost due to wind gusts), candy bags (92 %), lighters (75 %), and smaller sweet wrappers (64 %). Sweet wrappers were identified as being at the lower size limit of what could be captured with the larger grid. When only items larger than the grid size were considered, the recovery rate increased to 89 % (ARTLINCO, 2020).

Based on our experience with litter collection in Aarhus, these results appear reliable. Since the SPO installation in Aarhus covers 9.5 m of the 10 m wide channel, complemented by a guide arm (small metal groyne) to direct floating litter toward the center and prevent escape through the remaining 0.5 m on the south side, we assume that a recovery rate of 89 %—or potentially higher—for litter items larger than the grid size is a reasonable estimate. This, of course, is limited to litter on the water surface as the SPO's filtration unit only skims the surface layer (to a depth of around 30 cm).

However, it should be noted that small litter items, such as cigarette butts, snus pouches, and sweet wrappers, are often smaller than the 35 × 60 mm mesh of the SPO grid used in Aarhus. This makes it unlikely that all such items floating on the surface were captured. Consequently, the recorded quantities of small litter likely underestimate the actual amount present, as many pieces may have passed through the grid or been overlooked during analysis. Therefore, the observed decline in cigarette butts and other small items can only partly be attributed to behavioral or regulatory changes, since both the collection system and visual detection are both less effective for such items. Furthermore, as the litter analyses were conducted by different staff during the two monitoring periods, variations in accuracy may have occurred. Such variability is common across litter studies and represents an inherent source of uncertainty, particularly for smaller or lightweight materials that are more difficult to see.

4.8. Area of application for SeaProtectorOne (SPO)

In this study, the SPO (9.5 m) was deployed in a 10 m-wide channel. More broadly, the SPO can be used on wider rivers. It can be mounted on a quay or riverbank, or on a pile foundation, and set up in a staggered configuration from both banks. In a two-unit setup, it can cover river widths of up to 62 m while allowing vessel passage (ARTLINCO, 2020). SPO performance relies on continuous through-flow, with practical velocities spanning roughly 0.4–2.0 m/s. As waves can push litter away from the SPO, it is best to place it in an area protected from waves. SPO works in moderate to strong winds, but winds blowing against the current or across the base can reduce its retention capacity. When installed in windy areas, a windbreak can be installed to prevent this. At wind speeds of ≥ 12 m/s, the SPO initiates a discharge cycle and moves to a safe position (ARTLINCO, 2020).

5. Conclusion

This study demonstrates the value of continuous, high-resolution monitoring of floating macro-litter at the river–sea interface using an automated device that spans the full width of the Aarhus River channel. By collecting and categorizing over 80,000 pieces of litter across two

one-year monitoring periods, high-resolution datasets were produced on the inputs of riverine litter into the Baltic Sea. Plastic was the dominant litter category in both years, though paper/cardboard and metal also represented substantial shares. The ten most common litter items accounted for more than 75 % of all litter, with a strong presence of SUP and takeaway-related materials reflecting the urban origin of most of the litter.

A considerable reduction in floating macro-litter was observed, with total quantities falling by over 70 % between the two monitoring years. Temporal patterns from the first year revealed that pollution peaked on weekends and was highest during summer and autumn, underscoring the role of social and recreational activity in litter generation. However, in the second year only weekly data were available, which prevented the detection of such daily patterns. Furthermore, no strong seasonal differences were found in the second year.

The observed reduction in litter quantities is likely the result of multiple reinforcing factors, with the end of COVID-19 restrictions playing a role. As people spent less time socializing outdoors, consuming takeaways and using single-use packaging, less litter was generated and ended up in the river. This development was reinforced by EU-level measures such as the Single-Use Plastics Directive, as well as local initiatives in Aarhus, including reusable takeaway packaging systems and awareness-raising campaigns. Together, these factors highlight how both regulatory changes and societal shifts can substantially reduce urban riverine litter, while also showing the value of river-based interception for understanding and addressing marine litter inputs.

Building on these insights, future research should prioritise multi-year monitoring with daily resolution to enable robust comparisons and improved detection of temporal trends. For a complete mass balance of litter entering the sea, it would also be important to sample and quantify material in the water column and bed load, not only surface fractions. Incorporating litter weight in mass-balance calculations and conducting systematic recovery-rate tests could further enhance the reliability of such monitoring, ensuring that river-sea interfaces are accurately represented in marine-litter budgets and policymaking.

Animal ethics and consent to participate declarations

Not applicable.

CRediT authorship contribution statement

Mirco Haseler: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Geraldo Mihut:** Data curation, Investigation, Validation, Writing – review & editing, Formal analysis.

Consent for publication

The authors certify that the publisher is permitted to publish this work.

Ethical approval

All the authors have read, understood, and have complied as applicable with the statement on “Ethical responsibilities of Authors” as found in the Instructions for Authors.

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

During the preparation of this work the author(s) used ChatGPT and DeepL in order to refine the language.

Funding

This work was funded by the Interreg South Baltic Programme 2021–2027 within the scope of the project “Circular Ocean-bound Plastic” No. STHB.02.03-IP.01–0006/23–00.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors wish to acknowledge the employees of Teknik og Miljø for their valuable contribution in emptying the SeaProtectorOne and systematically recording the collected litter. Their effort was indispensable in ensuring both the progress and the quality of this project. Gratitude is further extended to Aarhus Municipality for generously providing free access to the SeaProtectorOne and thereby enabling the subsequent analysis of the collected litter. Finally, sincere appreciation is expressed to AllinOnGreen for supplying the 2021/2022 results, which made it possible to conduct a meaningful comparison with the newly generated data. We would also like to thank all Danish COP project partners who helped us find the local literature for the discussion.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.marpolbul.2025.118913>.

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

References

- Aarhus Kommune, 2024. Smid det i skraldespanden!. https://aarhus.dk/nyt/teknik-og-miljoe/2024/juni-2024/smid-det-i-skraldespanden?utm_source=chatgpt.com. (Accessed 27 August 2025).
- Aarhus Kommune, 2025. THE WATERFLOW SIDE: Water Level Today. <http://www.hydrometri.dk/kommune/aarhus/>.
- Addamo, A.M., Perrine, L., Hanke, G., 2017. Top Marine Beach Litter Items in Europe: A review and synthesis based on beach litter data. MSFD Technical Group on Marine Litter 2017.
- Andrady, A.L., 2011. Microplastics in the marine environment. *Mar. Pollut. Bull.* 62, 1596–1605. <https://doi.org/10.1016/j.marpolbul.2011.05.030>.
- Andriolo, U., Gonçalves, G., 2024. How much does marine litter weigh? A literature review to improve monitoring, support modelling and optimize clean-up activities. *Environ. Pollut. (barking, Essex: 1987)* 361, 124863. <https://doi.org/10.1016/j.envpol.2024.124863>.
- Andriolo, U., Gonçalves, G., 2025. Two decades of marine litter surveys on the North Atlantic Iberian coast: a spatial and temporal analysis of the OSPAR dataset for Portugal and Spain. *Mar. Pollut. Bull.* 218, 118210. <https://doi.org/10.1016/j.marpolbul.2025.118210>.
- Andriolo, U., Gonçalves, G., Hidaka, M., Gonçalves, D., Gonçalves, L.M., Bessa, F., Kako, S., 2024. Marine litter weight estimation from UAV imagery: three potential methodologies to advance macrolitter reports. *Mar. Pollut. Bull.* 202, 116405. <https://doi.org/10.1016/j.marpolbul.2024.116405>.
- ARTLINCO, 2020. SeaProtectorOne removal of plastic garbage from rivers and streams: findings and conclusions from test of SeaProtectorOne at the Tangevaerket dam. Test conducted in the period from 29th of april to 9th of july 2020.
- Bellou, N., Gambardella, C., Karantzalos, K., Monteiro, J.G., Canning-Clode, J., Kemna, S., Arrieta-Giron, C.A., Lemmen, C., 2021. Global assessment of innovative solutions to tackle marine litter. *Nat Sustain* 4, 516–524. <https://doi.org/10.1038/s41893-021-00726-2>.
- BLASTIC, 2018. Results and experiences from the plastic litter monitoring in the BLASTIC pilot areas: BLASTIC - plastic waste pathways into the Baltic Sea. WP3 results from plastic litter monitoring in the pilot areas.

- Cesarini, G., Crosti, R., Secco, S., Gallitelli, L., Scalici, M., 2022. From city to sea: spatiotemporal dynamics of floating macrolitter in the Tiber River. *Sci. Total Environ.*, 159713 <https://doi.org/10.1016/j.scitotenv.2022.159713>.
- Cheshire, A., Adler, E., Barbieri, J., 2009. UNEP/IOC guidelines on survey and monitoring of marine litter. United Nations Environment Programme, Regional Seas Programme; Intergovernmental Oceanographic Commission, integrated coastal area management and regional Programme, Nairobi, Paris xii (117).
- ClimateChart, 2024. Climate Chart of Aarhus, Denmark: Comprehensive Climate Chart of Aarhus. Monthly Averages and Weather Trends, Denmark. https://www.climechart.com/en/climate-chart/aarhus/denmark?utm_source=chatgpt.com (accessed 22 August 2025).
- Danish Environmental Protection Agency, 2025. Fastgjorte låg sparer miljøet for 126.000 kg. plastik om året: Dansk Retursystem's new statement shows that as many as 99% of all plastic bottles are now returned with the lid on. <https://mst.dk/nyheder/2025/februar/fastgjorte-laag-sparer-miljoet-for-126000-kg-plastik-om-aaret>. (Accessed 3 September 2025).
- Danish industry, 2025. The New Waste Requirements Have Come into Force: What Does it Mean for You? https://www.danskindustri.dk/medlemsforeninger/traesektion/nyheder/2025/1/de-nye-affaldskrav-trader-i-kraft-hvad-betyder-det-for-dig/?utm_source=chatgpt.com. (Accessed 3 September 2025).
- Dansk Retur System, 2025a. About Deposits. <https://danskretursystem.dk/en/about-deposits/>. (Accessed 28 August 2025).
- Dansk Retur System, 2025b. Where to Return Bottles and Cans - Learn More here. http://danskretursystem.dk/en/about-deposits/where-return/?utm_source=chatgpt.com. (Accessed 5 September 2025).
- Dittmann, S., Kiessling, T., Knickmeier, K., Schönberg, J., Brennecke, D., Hinzmann, M., Knoblauch, D., Thiel, M., 2024. Temporal variability of litter pollution of rivers in Germany - a long-term assessment by schoolchildren as citizen scientists. *Mar. Pollut. Bull.* 209, 117253. <https://doi.org/10.1016/j.marpolbul.2024.117253>.
- DR.DK, 2020. Most far-reaching ban in Denmark: Aarhus bans smoking at bus stops and other public areas.
- EPS Cycle, 2025. An European Mark of Commitment. <https://epsycle.org/>. (Accessed 3 September 2025).
- EU, 2019. DIRECTIVE (EU) 2019/904 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 5 June 2019 on THE reduction of the impact of certain plastic products on the environment: (text with EEA relevance). *Off. J. Eur. Union L* 155, 1.
- European Commission, 2025. Online Photo Catalogue of the Joint List of Litter Categories: Example Images to Support the Monitoring of Macro Litter in Different Environmental Matrices. <https://mcc.jrc.ec.europa.eu/main/photocatalogue.py?N=41&O=457&cat=pl>. (Accessed 22 March 2025).
- European Environment Agency, 2025. Impacts of COVID-19 on Single-Use Plastic in Europe's Environment. European Environment Agency's home page. <https://www.eea.europa.eu/en/analysis/publications/impacts-of-covid-19-on-single-use-plastic-in-europes-environment>. (Accessed 5 September 2025).
- Fallati, L., Polidori, A., Salvatore, C., Saponari, L., Savini, A., Galli, P., 2019. Anthropogenic marine debris assessment with unmanned aerial vehicle imagery and deep learning: a case study along the beaches of the Republic of Maldives. *Sci. Total Environ.* 693, 133581. <https://doi.org/10.1016/j.scitotenv.2019.133581>.
- Fleet, D., Vlachogianni, T., Hanke, G., 2021. A joint list of litter categories for marine macrolitter monitoring: manual for the application of the classification system. In: EUR 30348 EN, 2021. publications Office of the European Union, Luxembourg. <https://doi.org/10.2760/127473>.
- González-Fernández, D., Hanke, G., 2017. Toward a harmonized approach for monitoring of riverine floating macro litter inputs to the marine environment. *Front. Mar. Sci.* 4. <https://doi.org/10.3389/fmars.2017.00086>.
- González-Fernández, D., Hanke, G., RiLON network, 2018. Floating Macro Litter in European Rivers - Top Items: Review and synthesis of data collected by the JRC exploratory project RIMMEL. Technical report.
- González-Fernández, D., Cózar, A., Hanke, G., Viejo, J., Morales-Caselles, C., Bakiu, R., Barceló, D., Bessa, F., Bruge, A., Cabrera, M., Castro-Jiménez, J., Constant, M., Crosti, R., Galletti, Y., Kideys, A.E., Machitadze, N., Pereira de Brito, J., Pogojeva, M., Ratola, N., Rigueira, J., Rojo-Nieto, E., Savenko, O., Schöneich-Argent, R.L., Siedlewicz, G., Suaria, G., Tourgeli, M., 2021. Floating macrolitter leaked from Europe into the ocean. *Nat Sustain* 4, 474–483. <https://doi.org/10.1038/s41893-021-00722-6>.
- Hanke, G., Canals, M., Vescovo, V., MacDonald, T., Martini, E., Ruiz-Orejón, L.F., Galgani, F., Palma, M., Papatheodorou, G., Ioakeimidis, C., Sakellariou, D., Drakopoulou, P., Fakiris, E., 2025a. Marine litter in the deepest site of the Mediterranean Sea. *Mar. Pollut. Bull.* 213, 117610. <https://doi.org/10.1016/j.marpolbul.2025.117610>.
- Hanke, Georg, Walvoort, Dennis, Orejón, Luis Francisco Ruiz, Van Loon, Willem, Giorgetti, Alessandra, Molina-Jack, Eugenia, Vinci, Matteo, 2025b. European Coastline Macro Litter Trends 2015–2021: Methodology Development and Trend Results for the Marine Strategy Framework Directive. Publications Office, Luxembourg, p. 182.
- Haseler, M., Ben Abdallah, L., El Fels, L., El Hayany, B., Hassan, G., Escobar-Sánchez, G., Robbe, E., Thenen, M. von, Loukili, A., Abd El-Raouf, M., Mhiri, F., El-Bary, A.A., Schernewski, G., Nassour, A., 2025. Assessment of beach litter pollution in Egypt, Tunisia, and Morocco: a study of macro and meso-litter on Mediterranean beaches. *Environ. Monit. Assess.* 197, 123. <https://doi.org/10.1007/s10661-024-13517-x>.
- HDR, 2024. HDR AFFALDSANALYSE: Hold Danmark Rent. <https://www.holddanmarkrent.dk/media/bk0bf5j/%C3%A5rsrapport-hdr-2024.pdf>.
- JRC, 2011. Marine litter: Technical Recommendations for the Implementation of MSFD Requirements. MSFD GES Technical Subgroup on Marine Litter, Publications Office, Luxembourg, 1 online resource (91).
- Kelly, N.E., Feyrer, L., Gavel, H., Trela, O., Ledwell, W., Breeze, H., Marotte, E.C., McConney, L., Whitehead, H., 2023. Long term trends in floating plastic pollution within a marine protected area identifies threats for endangered northern bottlenose whales. *Environ. Res.* 227, 115686. <https://doi.org/10.1016/j.envres.2023.115686>.
- Kommune, Aarhus, 2019a. Høring – Røgfrie udearealer i Aarhus Kommune. https://delta.g.aarhus.dk/sites/default/files/documents/H%C3%B8ring%20E2%80%9320R%C3%B8gfrie%20udearealer%20i%20Aarhus%20Kommune_0.pdf. (Accessed 27 August 2025).
- Kommune, Aarhus, 2019b. Plastics Strategy City of Aarhus 2020-2025: prepared by the Department of Technical Services and Environment, City of Aarhus. Version 1, June 2019. https://www.au.dk/fileadmin/ingen_mappe_valgt/Plastic_strategy_Aarhus_City_2020-2025_ENG.pdf.
- Kredslob, 2025. Waste and Recycling in English. https://www.kredslob.dk/privat/ge-nbrug-og-affald/waste-and-recycling?utm_source=chatgpt.com. (Accessed 5 September 2025).
- Kühn, S., Bravo Rebolledo, E.L., van Franeker, J.A., 2015. Deleterious effects of litter on marine life: Susanne Kühn, Elisa L. Bravo Rebolledo and Jan a. van Franeker. In: Bergmann, M., Gutow, L., Klages, M. (Eds.), *Marine Anthropogenic Litter*. Springer International Publishing, Cham.
- Law, K.L., 2017. Plastics in the marine environment. *Annu. Rev. Mar. Sci.* 9, 205–229. <https://doi.org/10.1146/annurev-marine-010816-060409>.
- Lebreton, L.C.M., van der Zwet, J., Damsteeg, J.-W., Slat, B., Andrady, A., Reisser, J., 2017. River plastic emissions to the world's oceans. *Nat. Commun.* 8, 15611. <https://doi.org/10.1038/ncomms15611>.
- Letbanen, 2024. Smid det i skraldespanden!. https://www.letbanen.dk/nyheder/2024/smid-det-i-skraldespanden/?utm_source=chatgpt.com. (Accessed 4 September 2025).
- Lincoln, S., Andrews, B., Birchenough, S.N.R., Chowdhury, P., Engelhard, G.H., Harrod, O., Pinnegar, J.K., Townhill, B.L., 2022. Marine litter and climate change: inextricably connected threats to the world's oceans. *Sci. Total Environ.* 837, 155709. <https://doi.org/10.1016/j.scitotenv.2022.155709>.
- Mcllgorm, A., Raubenheimer, K., Mcllgorm, D.E., Nichols, R., 2022. The cost of marine litter damage to the global marine economy: insights from the Asia-Pacific into prevention and the cost of inaction. *Mar. Pollut. Bull.* 174, 113167. <https://doi.org/10.1016/j.marpolbul.2021.113167>.
- Meijer, L.J.J., van Emmerik, T., van der Ent, R., Schmidt, C., Lebreton, L., 2021. More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean. *Sci. Adv.* 7. <https://doi.org/10.1126/sciadv.aaz5803>.
- meteoblue, 2025. Simulated Historical Climate & Weather data for Aarhus: Central Jutland, Denmark, 56.16°N 10.21°E, 10m asl. https://www.meteoblue.com/en/weather/historyclimate/climatemodellert/aarhus_denmark_2624652. (Accessed 24 February 2025).
- Ministry of the Environment and Gender Equality, 2020. LAW No 61 of 28/01/2020 Act amending the Act on Environmental Protection and the Packaging Tax.
- MSFD TSG ML, 2023. Guidance on the monitoring of marine litter in European seas: an update to improve the harmonised monitoring of marine litter under the marine strategy framework Directive. Publications Office of the European Union. <https://doi.org/10.2760/59137>.
- Newbould, R.A., Powell, D.M., Whelan, M.J., 2022. Macroplastic Debris Transfer in Rivers: A Travel Distance Approach. <https://doi.org/10.3389/frwa.2021.724596>.
- Olsen, S., 2002. *Danmarks søer og åer*. Politikens Forlag.
- OWOO, 2012. Plastics Breakdown Sources. One World one Ocean. https://www.oneworldocean.com/images/blog/PlasticsInfographic_Sources.pdf. (Accessed 4 June 2019).
- Panti, C., Bains, M., Lusher, A., Hernandez-Milan, G., Bravo Rebolledo, E.L., Unger, B., Syberg, K., Simmonds, M.P., Fossi, M.C., 2019. Marine litter: one of the major threats for marine mammals. Outcomes from the European cetacean society workshop. *Environmental pollution (barking, Essex: 1987)* 247, 72–79. <https://doi.org/10.1016/j.envpol.2019.01.029>.
- Peng, G., Bellerby, R., Zhang, F., Sun, X., Li, D., 2020. The ocean's ultimate trashcan: Hadal trenches as major depositories for plastic pollution. *Water Res.* 168, 115121. <https://doi.org/10.1016/j.watres.2019.115121>.
- PPWR, 2025. Fact Sheet: Reusable Take-Away Packaging: 7 Reasons why Reusable Take-Away Packaging Is a Sustainable Alternative for Climate Protection and Resource Conservation.
- Public Health Ontario, 2022. Public Health Measures and COVID-19 Epidemiology in Select International Jurisdictions (Current up to June 6, 2022) (Queen's Printer for Ontario).
- Reisser, J., Shaw, J., Wilcox, C., Hardesty, B.D., Proietti, M., Thums, M., Pattiaratchi, C., 2013. Marine plastic pollution in waters around Australia: characteristics, concentrations, and pathways. *PLoS One* 8, e80466. <https://doi.org/10.1371/journal.pone.0080466>.
- REUSEABLE, 2025. About the REUSEABLE Project. <https://www.reuseable.dk/about-us>. (Accessed 4 September 2025).
- Riegels, N., Lynggaard-Jensen, A., Krogsgaard Jensen, J., Gerner, N.V., Anzaldúa, G., Mark, O., Butts, M., Birk, S., 2020. Making the ecosystem services approach operational: a case study application to the Aarhus River, Denmark. *Sci. Total Environ.* 707, 135836. <https://doi.org/10.1016/j.scitotenv.2019.135836>.
- Schernewski, G., Radtke, H., Hauk, R., Baresel, C., Olshammer, M., Osinski, R., Oberbeckmann, S., 2020. Transport and behavior of microplastics emissions from urban sources in the Baltic Sea. *Front. Environ. Sci.* 8, 579361. <https://doi.org/10.3389/fenvs.2020.579361>.
- Schernewski, G., Escobar Sánchez, G., Felsing, S., Gatel Rebours, M., Haseler, M., Hauk, R., Lange, X., Piehl, S., 2024. Emission, transport and retention of floating marine macro-litter (plastics): the role of Baltic Harbor and sailing festivals. *Sustainability* 16, 1220. <https://doi.org/10.3390/su16031220>.

- Schmidt, C., Krauth, T., Wagner, S., 2017. Export of plastic debris by Rivers into the sea. *Environ. Sci. Technol.* 51, 12246–12253. <https://doi.org/10.1021/acs.est.7b02368>.
- Schreyers, L., van Emmerik, T., Nguyen, T.L., Phung, N.-A., Kieu-Le, T.-C., Castrop, E., Bui, T.-K., Strady, E., Kosten, S., Biermann, L., van den Berg, S., van der Ploeg, M., 2021. A Field Guide for Monitoring Riverine Macroplastic Entrapment in Water Hyacinths, 18 pp.
- Schwarz, A.E., Ligthart, T.N., Boukris, E., van Harmelen, T., 2019. Sources, transport, and accumulation of different types of plastic litter in aquatic environments: a review study. *Mar. Pollut. Bull.* 143, 92–100. <https://doi.org/10.1016/j.marpolbul.2019.04.029>.
- SDU, 2025. Danskernes rygevaner 2024: Rapporten er udarbejdet af Statens Institut for Folkesundhed. Syddansk Universitet på vegne af Sundhedsstyrelsen, Rapporten er udarbejdet af Statens Institut for Folkesundhed. <https://www.sst.dk/-/media/Udgifter/2025/Danskernes-rygevaner/Danskernes-Rygevaner-2024.ashx> (accessed 27 August 2025).
- Serra-Gonçalves, C., Lavers, J.L., Bond, A.L., 2019. Global review of beach debris monitoring and future recommendations. *Environ. Sci. Technol.* 53, 12158–12167. <https://doi.org/10.1021/acs.est.9b01424>.
- Statistik, Danmark, 2024. Statistikbanken Borgere: BY1: Befolkningen 1. januar efter byområder, landdistrikter, alder og køn. <https://www.statistikbanken.dk/BY1>. (Accessed 21 February 2025).
- Tasseron, P., Zinsmeister, H., Rambonnet, L., Hiemstra, A.-F., Siepman, D., van Emmerik, T., 2020. Plastic hotspot mapping in urban water systems. *Geosciences* 10, 342. <https://doi.org/10.3390/geosciences10090342>.
- Tasseron, P., Begemann, F., Joosse, N., van der Ploeg, M., van Driel, J., van Emmerik, T., 2023. Amsterdam urban water system as entry point of river plastic pollution. *Environ. Sci. Pollut. Res.* 30, 73590–73599. <https://doi.org/10.1007/s11356-023-26566-5>.
- The Atlantic, 2022. How Denmark decided COVID isn't a critical threat to society. https://www.theatlantic.com/ideas/archive/2022/02/denmark-covid-restrictions/621482/?utm_source=chatgpt.com.
- UNEP, 2015. Marine Litter Assessment in the Mediterranean.
- UNEP, 2021. From Pollution to Solution. A global assessment of marine litter and plastic pollution. https://gridarendal-website-live.s3.amazonaws.com/production/documents/s_document/865/original/MLGA_EN_V6-updated-21102021.pdf?1634815204.
- van Emmerik, T., Schwarz, A., 2020. Plastic debris in rivers. *WIREs Water* 7, e1398. <https://doi.org/10.1002/wat2.1398>.
- van Emmerik, T., Kieu-Le, T.-C., Loozen, M., van Oeveren, K., Strady, E., Bui, X.-T., Egger, M., Gasperi, J., Lebreton, L., Nguyen, P.-D., Schwarz, A., Slat, B., Tassin, B., 2018. A methodology to characterize riverine macroplastic emission into the ocean. *Front. Mar. Sci.* 5, 372. <https://doi.org/10.3389/fmars.2018.00372>.
- van Emmerik, T., Mellink, Y., Hauk, R., Waldschläger, K., Schreyers, L., 2022. Rivers as plastic reservoirs. *Front. Water* 3, 786936. <https://doi.org/10.3389/frwa.2021.786936>.
- van Emmerik, T.H.M., Frings, R.M., Schreyers, L.J., Hauk, R., Lange, S.I. de, Mellink, Y.A.M., 2023. River plastic transport and deposition amplified by extreme flood. *Nat. Water* 1, 514–522. <https://doi.org/10.1038/s44221-023-00092-7>.
- VisitAarhus, 2025. REUSEABLE To-Go-Cups in Aarhus. https://www.visitaarhus.com/aarhus-region/plan-your-trip/reuseable-go-cups-aarhus-gdk1142559?utm_source=chatgpt.com. (Accessed 4 September 2025).
- Winton, D., Marazzi, L., Loiseau, S., 2022. Drivers of public plastic (mis)use - new insights from changes in single-use plastic usage during the Covid-19 pandemic. *Sci. Total Environ.* 849, 157672. <https://doi.org/10.1016/j.scitotenv.2022.157672>.
- Winton, D.J., Anderson, L.G., Roccliffe, S., Loiseau, S., 2020. Macroplastic pollution in freshwater environments: focusing public and policy action. *Sci. Total Environ.* 704, 135242. <https://doi.org/10.1016/j.scitotenv.2019.135242>.