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Sources and Leakages of Microplastics in Cruise Ship Wastewater

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To date, the contribution of sea-based sources to the global marine litter and plastic pollution problem remains poorly understood. Cruise ships produce large amounts of wastewater and concentrate their activities in fragile and ecologically valuable areas. This paper explores for the first time the sources of microplastics in cruise ship wastewater, as well as their pathways from source to sea. It thereto uses a novel approach for the identification of sources and pathways, based on scientific literature on microplastic sources and pathways, literature on cruise operations and wastewater management as well as a questionnaire among cruise lines. The study highlights personal care and cosmetic products, cleaning and maintenance products and synthetic microfibers released from textiles in laundry as relevant source categories. Untreated grey water and the overboard discharge of biosludge, resulting from the treatment of sewage and grey water, were identified as key pathways. Cruise lines can reduce microplastic emissions by adapting their purchasing policies for personal care, cosmetic, cleaning and maintenance products and professional textiles. In addition, the holistic management of all wastewater streams and resulting waste products is essential to prevent leakages of microplastics from cruise ships to vulnerable coastal and marine ecosystems. Furthermore, the approach can be used to guide company-level assessments and can be modified to address microplastic leakages in other maritime sectors.

Keywords: cruise ships, microplastics, wastewater, sea-based sources, marine litter, plastic pollution, marine pollution, shipping

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1 INTRODUCTION

Marine litter is a problem of emerging concern and research efforts as well as initiatives to address the problem are developing rapidly (UNEP, 2021). Recently, a breakthrough was achieved at the United Nations Environments Assembly (UNEA-5.2), where 175 nations committed to forge an international legally binding agreement to end plastic pollution by 2024, addressing the full lifecycle of plastic from source to sea[1]. Marine litter is defined as "any persistent, manufactured or processed

[1] https://news.un.org/en/story/2022/03/1113142

solid material discarded, disposed of or abandoned in the marine and coastal environment" (UNEP, 2021). While the term embraces different types of materials, plastics constitute the largest proportion (Galgani et al., 2015). Jambeck et al. (2015) estimated that in 2010, 4.8 to 12.7 million MT of plastics entered the ocean, and inputs are expected to increase over the coming decades (Lebreton and Andrady, 2019). Plastic can travel long distances and is found in all parts of the marine ecosystem, even in very remote locations such as in Arctic sea ice (Obbard et al., 2014) and the Mariana Trench (Chiba et al., 2018). Microplastics (MPs) are small pieces of plastic, with a size smaller than 5 mm. MPs comprise both manufactured microscopic plastic particles (primary MPs), such as microbeads with applications in the cosmetic industry and industrial pellets used for the production of plastics, and particles that result from the abrasion and degradation of larger items (secondary MPs) (Cole et al., 2011). MPs in the marine environment can be ingested or inhaled through the gills by a wide range of organisms (Wright et al., 2013; GESAMP, 2016; Hantoro et al., 2019). Once ingested, MPs may block or damage intestinal tracts (Cole et al., 2011; Wright et al., 2013). They can also be absorbed through the gut walls (Foley et al., 2018). In addition, MPs may leach toxic pollutants, including chemicals that are intentionally added during plastic production as well as organic contaminants and heavy metals that sorb to the MP surface (Teuten et al., 2009; Rochman et al., 2014). Impacts that have been associated with MP ingestion in marine biota include adverse effects on feeding (e.g. Wegner et al., 2012), growth (e.g. Au et al., 2015), reproduction (e.g. Della Torre et al., 2014) and survival (e.g. Luís et al., 2015). Besides the effects at the individual level, MPs as well as pollutants absorbed by MPs, can be transferred through food webs (Farrell and Nelson, 2013; Setälä et al., 2014) and induce ecological impacts (Rochman et al., 2016). Human health may also be affected by MPs in the marine environment through the consumption of contaminated seafood (Hantoro et al., 2019; Campanale et al., 2020).

In order to effectively address marine litter and (micro-)plastics, it is necessary to understand the contribution of individual sources and the pathways from these sources to the environment. Assessing the origin of MPs in the environment is complicated (Hardesty et al., 2017) and the relative contribution of different sources and pathways is strongly dependent on local conditions (Duis and Coors, 2016). While it is generally assumed that most marine litter derives from land-based sources, the contribution from sea-based source varies strongly by geographic location and could be substantial for specific locations (GESAMP, 2021). Knowledge about sea-based sources is still little developed compared to land-based sources; the GESAMP (Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection) Working Group on sea-based sources of marine litter concluded that knowledge of the type, quantity and impact of sea-based sources is lacking (GESAMP, 2021), thus hindering the development of effective mitigation strategies. Ship-based sources contribute to MP pollution, e.g. through paints and coatings, abrasives used for the cleaning of ship hulls during maintenance, loss of cargo (e.g. plastic pellets) and discharges of wastewater (Boucher and Friot, 2017; Bray, 2019; GESAMP, 2021). In terms of wastewater, cruise ships would be of particular interest because of the large quantities of wastewater that are generated on board these ships (GESAMP, 2021). Vicente-Cera et al. (2019a) estimate that the world cruise fleet produced about 34.000.000 m^3 of wastewater in 2017; a production rate that is comparable to that of the country Cyprus[2].

Until the start of the COVID-19 pandemic, the cruise industry had shown a constant growth, from 17.8 million passengers in 2009 to 29.7 million passengers in 2019[3]: an increase of 75% in 10 years. The pandemic led to a complete halt of operations; however, the industry expects a full recovery compared to 2019 levels by 2023 and a growth of 12% by 2026[4]. Currently, the largest cruise ship in operation can carry up to 6988 passengers and 2300 crew members[5]. Besides a means of transportation and accomodation, cruise ships typically provide a wide array of onboard services and attractions to their passengers, such as swimming pools, spas, theatres and sports facilities. The main mainstream cruise destinations are located the Caribbean, the Mediterranean and Northwestern Europe; specialty "adventure" types of cruises attend extremely remote and vulnerable environments (Lamers et al., 2015) such as the Arctic and Antarctic. Around 70% of the cruise destinations are located in biodiversity hotspots (Lamers et al., 2015) and cruise ships frequently pass through fragile coastal and shallow areas as well as marine protected areas, especially when entering or leaving ports (Lloret et al., 2021). Caric et al. (2019) highlight that in the Mediterranean, cruise ships frequently anchor in close proximity of many marine protected areas (MPAs) and the heavily trafficked cruise port of Venice is even located within such a site. Considering that cruise activities typically concentrate in certain coastal areas and routes, these vulnerable areas are exposed to cumulative environmental impacts of these activities (Toneatti et al., 2020). With increasing cruise intensity, the impacts of the industry, including MP pollution, are likely to increase in the coastal and marine environment.

This study aims to highlight characteristics of the cruise sector that affect the potential for MPs being found in wastewater discharges, and provide recommendations to guide and set-up future research efforts as well as indicate general directions for mitigation. It thereto uses a novel approach for the identification of these sources and pathways, based on scientific literature on MP sources and pathways, literature on cruise operations and wastewater management as well as a questionnaire among cruise lines. First, an inventory was made of sources of MPs in the marine environment, based on general scientific literature. From this general inventory those sources were selected that are relevant to cruise operations and additional source categories were identified based on the characteristics of cruise operations and facilities. Subsequently, the identified sources were linked to the different wastewater streams and finally the management of each of these wastewater streams was evaluated.

[2] https://www.fao.org/aquastat/en/databases/maindatabase/

[3] https://www.statista.com/topics/1004/cruise-industry/#dossierKeyfigures

[4] https://cruising.org/en-gb/news-and-research/research/2022/january/state-of-the-cruise-industry-outlook-2022

[5] https://www.royalcaribbeanpresscenter.com/fact-sheet/34/wonder-of-the-seas/).

2 MATERIALS AND METHODS

Figure 1 presents an overview of the methodology for the identification of sources and pathways of MPs in cruise ship wastewater (detailed descriptions of the steps are described in the following paragraphs). Here, the term "sources" refers to the different applications of plastics and synthetic polymers on board cruise ships that have the potential to release. MPs to the marine environment. Through different release mechanisms, MPs find their way to the wastewater streams. Pathways are defined as the routes through which MP particles are transported to the marine environment, where the scope of this research is restricted to pathways through cruise ship wastewater discharges.

2.1 Literature Review of Microplastic Sources

Since cruise ships are often characterized as "floating cities", it was reasoned that MP sources on cruise ships have significant overlap with land-based urban sources of MPs. In addition, the maritime operations as well as any aspects that are unique to the cruise industry should be addressed. To identify and characterize sources of MPs, the research is based on the approach that was applied in different European countries, the European Union and the OSPAR region, as reported by Sundt et al. (2014); Lassen et al. (2015); Essel et al. (2015); Magnusson et al. (2016); Scudo et al. (2017); Verschoor et al. (2017) and Hann et al. (2018). These studies estimate MP emissions at a local or regional scale, based on the sources and pathways of MPs reported in general literature in combination with local data on plastic uses and other relevant local factors. Lassen et al. (2015) define eight categories of primary MP sources and six categories of secondary MP sources, and identified the pathways from these sources to surface waters. This structure was adopted and the list was complemented with the results of other studies, reflecting all reported land-based and sea-based MP sources and pathways at national or regional level. Next, sources were selected that could be relevant for cruise ship wastewater during normal operations.

2.2 Cruise-Specific Functionalities

In order to cover all sources of MPs that are specific to the cruise industry, the following overarching types of MP sources were considered, representing different functionalities of cruise ships: *cruise ship facilities*, *ship stores* and *people*. Cruise ship facilities were further divided into *hotel facilities* and *ship facilities*, in accordance with the structure proposed by Lois et al. (2004). The proposed facilities were supplemented by consulting Vogel et al. (2012) and Gibson and Parkman (2019), as well as by studying the deck plans of the ten largest cruise ships in the world, in order to cover the main facilities that are present on modern cruise ships. *Stores* comprise the different purchasing streams of cruise ships: fuel, corporate, technical and hotel purchasing (Véronneau and Roy, 2009). Finally, personal belongings of passengers and crew may act as MP sources; these are covered by the category "*people*".

2.3 Inventory of Microplastic Sources

Following the identification of the main MP source categories on board cruise ships, the inventory as derived from the literature study was further developed and supplemented to cover those categories that have relevance to cruise ships. This was done by crosschecking the identified categories as derived from literature on the one hand and the identified facilities, stores and people categories from the previous step on the other. This approach resulted in the elimination of some of the MP sources that were identified in the previous step, because of differences in the characteristics of these sources on board cruise ships compared to the general characteristics that are described in literature. On the other hand, cruise-specific sources were added to the general inventory. The contribution of specific facilities and stores to MP pollution is not always straightforward and requires a thorough understanding of operations, facilities and the types of stores. The details of many specific cruise operations are not extensively reported in literature, and only to a limited extent in grey literature. Therefore, in order to assess the relevance of the different facilities and stores, Google searches were used to

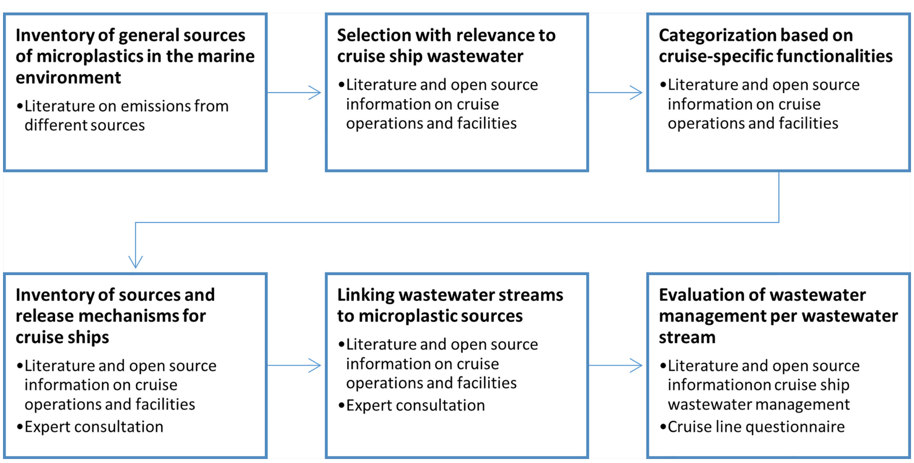

FIGURE1 | Research steps in the identification of sources and pathways of microplastics in cruise ship wastewater.

identify open access online resources, such as deck plans and pictures of the 10 largest cruise ships (e.g. to understand the application of artificial grass and the organization of laundry facilities) as well as blogs and YouTube videos, concerning the specific cruise ship operations and facilities such as laundry installations and engine room operations. In addition, experts were consulted to verify the findings (see below).

2.4 Linking Wastewater Streams to Microplastic Sources

In order to establish links between the sources on the one hand and wastewater streams on the other, the different sub-streams of the wastewater streams were identified based on literature. Then, the pathways from the identified sources to the different wastewater streams were assessed, by crosschecking each of the sources to the identified wastewater streams and vice versa.

2.5 Wastewater Management

The objective of this step was to map the main routes of the different wastewater streams and the key characteristics of treatment processes, where applicable, in order to identify potential pathways of MPs from the different wastewater streams. In addition, the characteristics of common treatment technologies were described. The assessment is based on scientific literature as well as grey literature. In order to verify the findings based on the grey literature, experts were consulted and a questionnaire was distributed among cruise lines.

2.6 Expert Consultation and Questionnaire

A preliminary version of the inventory of sources and pathways of MPs on board cruise ships was reviewed by experts in the fields of marine litter (3 experts) and MPs in onshore wastewater (1 expert). The typical practices and systems for wastewater management on board cruise ships were discussed with two experts in the field of maritime wastewater management and one cruise industry representative. In addition, a questionnaire was developed and distributed among cruise lines to verify the preliminary findings and collect additional industry-specific information. The questionnaire was distributed in February 2020 to the environmental managers of different cruise lines through the Cruise Lines International Association (CLIA). It consisted of a general section, where respondents could indicate the fleet size, a general wastewater management section and sections related to different wastewater treatment technologies. The final section concerned the measures and policies addressing MPs in wastewater.

2.7 Analysis and Interpretation of Results

This research involved different types of information and data, from different fields of research as well as use of a questionnaire and expert interviews. In order to organize these data, the research was structured around the existing frameworks from literature for the inventory of general MP sources as well as cruise facilities. In addition, the identified wastewater streams and related wastewater management practices were described in tabular form. These frameworks were then combined into matrices in order to structure the available information and to ensure that all relevant topics were covered through crosschecking. This structure guided the more detailed part of the research, and in particular the identification of cruise-specific MP sources. Where scientific literature was lacking, secondary resources were considered.

3 RESULTS

3.1 Literature Review of Microplastic Sources

Tables 1, **2** present the overview of main source groups of primary and secondary MPs in the marine environment, modified from Lassen et al. (2015), and extended with the results from other studies (indicated in the table, where applicable). The column on the right indicates whether the listed source groups were considered relevant for cruise ship wastewater. MP sources that were not considered relevant include raw materials for plastic production, industrial and professional handling processes of plastics, emissions from road traffic (tires, brake pads, bitumen and road paint), agricultural, aquaculture and oil and gas applications, typical onshore waste management issues (illegal waste burning, landfills and dumps), as well as the fragmentation of macroplastics in the environment due to natural processes. Also, the blasting of the ship hull during large scale maintenance with plastic abrasives is not further considered as blasting is not part of normal ship operations. Furthermore, Lassen et al. (2015) includes a separate category of primary MP emissions from paints through the washing of brushes. This source group was not considered applicable to cruise ships since this is mainly relevant for "do it yourself" and not for industrial practices (Verschoor et al., 2016). The category other includes plastic beads used in professional dish washing machines, plastic beads and ironing beads used by children, printer toner, specialty chemicals in wastewater treatment facilities (Scudo et al., 2017) and oil and gas industry (Sundt et al., 2014).

3.2 Cruise-Specific Functionalities

3.2.1 Facilities

Tables 3 and **4** give an overview of the typical hotel facilities and ship facilities as present on contemporary cruise ships, based on Lois et al. (2004). The overview is not exhaustive and may not be representative for all cruise ships but is indicative of the main systems and facilities present on ships, with the purpose to identify potential sources of MPs throughout the vessel.

3.2.2 Stores

Cruise ships carry stores of various types. Such stores include fuel and ship maintenance products for ship operations as well as food, potable water and detergents for hotel operations. Véronneau and Roy (2009) distinguish the following main purchasing streams of cruise ships: fuel, corporate, technical and hotel purchasing. Fuel purchasing covers fuel and other petroleum products for daily consumption, such as lubricants. Corporate items relate to office related materials such as office supplies and computers. Technical items include items for facility and ship maintenance, e.g. engine parts, electronic components and carpeting materials. Consumable items and food required for hotel operations fall under the category

TABLE 1 | Generic primary MP sources, modified from (Lassen et al., 2015) and indicating relevance to cruise ships.

Source group	Relevance
Raw materials for production of plastic items (plastic pellets)	No
Plastic particles used for cosmetics	Yes
Plastic particles in abrasive media	No
Plastic particles in cleaning and maintenance products	Yes
Plastic particles used in paints	Yes
Rubber granules and powder from recycling of tires	Yes
Expanded Polystyrene beads used for other applications than plastics production	Yes
Plastic particles used in medical and dentist products and in research	Yes
Plastic particles used in other applications	Yes

TABLE 2 | Generic secondary MP sources, modified from (Lassen et al., 2015) with descriptions and relevance to cruise ships..

Release mechanism	Source group	Relevance
Industrial activities	Plastic items	No
Particles released from plastic	Plastic items used indoors and	Yes
items during use	outdoors	Yes
	Textiles	Yes
		Yes
	Tires	No
	Automotive brake dust	No
	Polymer modified bitumen	No
	Artificial turfs	Yes
	Plastic film used in agriculture	No
	Plastic in fishing and aquaculture	No
	gear	No
Particles released from painted	Paint for indoor and outdoor	Yes
surfaces	applications	
	Paint for marine applications	Yes
	Road paint	No
Waste handling	Plastic waste and waste	No
	contaminated with plastics	Yes
		Yes
		No
	Illegal waste burning	No
	Landfills and waste dumps	No
Fires	Fires	No
Fragmentation of plastic waste	Terrestrial waste handling	No
in the environment	Maritime waste handling	Yes

of hotel purchasing. Furthermore, fresh water is a key resource on board.

3.2.3 People

Passengers and crew bring their personal belongings in their luggage. Significant categories are likely to include personal clothing, shoes, flipflops, personal toiletries and medication, electronics, books, suitcases and backpacks and snacks. People with children may bring plastic and inflatable toys. Furthermore, souvenirs bought ashore are brought on board after port visits.

3.3 Inventory of Sources and Release Mechanisms

Overviews of key MP sources and release mechanisms of both primary and secondary MPs on board cruise ships are displayed in **Tables 5** and **6**. The categories from Lassen et al. (2015) were revised to reflect both the general categories as found in literature as well as the relevance of these categories for cruise operations.

The main source groups for primary MPs (**Table 5**) are personal care & cosmetics, cleaning & maintenance and medical & pharmaceutical. Potential release mechanisms are mainly related to the use of products in "wet" applications, e.g. rinse-off bath and shower products, spa treatments, wet cleaning, dish washing, laundry and wastewater treatment. Other release mechanisms include medication use, medical and dental treatments, printing and damage of user products that contain primary MPs, e.g. polystyrene pellets or beads. In addition, certain shipboard wastewater treatment systems use flocculants (EPA, 2011; Chen et al., 2022), which could be polymer-based. The detailed assessment of cruise ship facilities led to the exclusion of rubber granules from artificial turfs as a source of primary MPs: no examples could be found of high impact sport facilities on board cruise ships that would require "third generation turfs" using a performance infill of (synthetic) rubber granules for shock absorption (Hann et al., 2018).

The identified release mechanisms for secondary MPs (**Table 6**) include the wear and damage of products during normal use, laundry and cleaning of textiles, wear and damage of painted surfaces, waste handling and littering. Sources embrace all plastic and synthetic items and surfaces on board the vessel, including paints and waste.

3.4 Linking Wastewater Streams to Microplastic Sources

The main wastewater streams that are produced on board cruise ships are sewage, grey water and oily bilge water. Sewage is the wastewater from toilets and primarily consists of human body wastes and water and may on some ships be mixed with wastes from medical facility sinks and drains (EPA, 2008). The International Convention for the Prevention of Pollution from Ships (MARPOL) covers the international regulations for sewage in Annex IV of the convention. According to these regulations, sewage may be discharged overboard without treatment outside coastal zones, provided that the ship maintains a minimum sailing speed of 4 knots. The average sewage generation rate is estimated at 68 l/person/day (Vicente-Cera et al., 2019a). Grey water consists of the wastewater streams from shower and bath, accommodation sinks, laundry, dishwashers and galleys (EPA, 2008). Wastewater from these sources is in practice often mixed with wastewater from other sources, such as drainage from drains and sinks in non-engine room spaces, food pulper effluents and wastewater from whirlpools (EPA, 2008). Unlike sewage, grey water discharges are not internationally regulated. Vicente-Cera et al. (2019a) estimate the average generation rate throughout the industry at 160 l/person/day. EPA (2008) defines oily bilge water as "the mixture of water, oily fluids, lubricants, cleaning fluids, and other similar wastes that accumulate in the lowest part of a vessel from a variety of different sources including engines (and other parts of the propulsion system), piping, and other mechanical and operational sources found throughout the machinery spaces of a vessel". International regulations, covered by MARPOL Annex I, allow discharges of oily bilge water at sea, provided that approved oil filtering

TABLE 3 | Hotel facilities on board cruise ships [adapted from Lois et al. (2004)].

Passenger facilities	Crew facilities	Entertainment facilities	Service facilities	Others
Staterooms/cabins	Cabins	Pools	Receptions and information desks	Medical center
Stairways and halls	Messes and bars	Whirlpools/solarium	Conference rooms	Shops
Public elevators	Recreation and internet areas	Spas	Offices	Beauty salon
Public areas (indoor)	Gym	Slides, flow-riders	Restaurants and bars	Nursery
Public areas (outdoor)	Galleys	Gym	Galleys, food preparation areas	Photo shop
	Launderettes	Sport fields, running tracks	Food storehouses	Print shop
	Store	Casino	Service elevators	Internet
	Crew office	Theaters	Bell box (room service)	Self-service launderettes
	Stairs and corridors	Cinemas	Housekeeping facilities	
		Nightclub	Laundry and dry-cleaning	
		Games area		
		Kids recreation areas		
		Mini golf		
		Climbing wall		
		Ice rink		
		Walkways and ziplines		
		Bowling		

TABLE 4 | Ship facilities on board cruise ships [adapted from Lois et al. (2004)].

Comfort system	Machinery	Tanks	Navigation	Decks and gear	Safety
Electricity infrastructure	Main engines	Fuel and oil	Bridge	Mooring equipment	Lifeboats
HVAC	Generators	Fresh water	Navigation equipment	Anchoring equipment	Life rafts
Fresh water generation and distribution	Transmission	Wastewater		Gangways	Fire-fighting system
Waste management systems	Control room	Ballast tanks		Helideck	Detectors and alarms
Stores of technical parts, paints etc.	Propellers/pods	Bilges		Open deck spaces	Low-level lighting
	Steering gear	Sludge tanks			Life jackets

equipment is used. The oil residue from the filtering process is to be stored in dedicated oil sludge tanks and delivered to port reception facilities (PRF). Vicente-Cera et al. (2019a) estimate that the average industry generation rate is 23 l per nautical mile.

In order to link the different wastewater streams to MP sources, the identified wastewater streams were divided into different sub-streams, each reflecting potential entry routes of MPs into wastewater. The left-hand side of **Table 7** summarizes the main sub-streams of which the wastewater streams consist. On the right-hand side, the primary MP source categories (as listed in **Table 5**), as well as the typical types of secondary MPs of relevance to these (sub-)streams are listed.

TABLE 5 | Primary microplastic sources and release mechanisms with relevance to cruise ship wastewater.

Source group	Sources	Release mechanism
Personal care & cosmetics	Stores: soaps and disinfecting agents in dispensers for hand washing/cleansing	Application of product
	Stores: spa, salon and nursery specialty products	Application of product
	Stores: products for sale in onboard shops	Application of product
	Stores: complimentary products provided in passenger cabins and showers in public facilities (gym, spa, etc.)	Application of product
	People: products brought on board by passengers and crew	Application of product
Cleaning & maintenance	Stores: cleaning products for wet cleaning of floors and surfaces	Use of products
	Stores: cleaning products for cleaning toilets	Use of products
	Stores: laundry detergents	Use of products
	Stores: dishwashing detergents	Use of products
	Stores: professional hand soaps	Use of products
	Stores: detergents for wet cleaning of specialty equipment and products	Use of products
	Stores: machinery and equipment maintenance products	Use of products for machinery and equipment maintenance
Medical & pharmaceutical	Stores: medical stores	Medical and dental treatments
	People: personal medication	Medication use
Other	Facilities: expanded polystyrene pellets in products	Damage of products
	Stores: wastewater flocculants and similar plastic-based products	Use of products
	Stores: printer toners	Spill of printer toner, printing dust
	Stores/people: beads	Loss of beads during use

The results demonstrate that the MP sources attributed to the different wastewater streams vary significantly. The MP content in sewage derives from pharmaceuticals and detergents used for the cleaning of toilets as well as larger items that are disposed in toilets. The MP sources related to grey water include personal care and cosmetic products (PCCP), detergents used for cleaning, dishwashing and laundry, fibers from synthetic textiles and the secondary MPs that are removed by wet cleaning. Finally, the MP sources attributed to oily bilge water mainly relate to engine room operations, which may involve various products for the cleaning, maintenance and operation of machinery that contain primary MPs. In addition, the different sub-streams of oily bilge water collect solid waste and dust, including plastics and secondary MPs, on their way to the bilges.

3.5 Wastewater Management

3.5.1 Sewage and Grey Water

There exist two categories of treatment systems that are relevant to sewage and grey water. Older ships are typically fitted with sewage treatment plants (STP), generally referred to as Marine Sanitation Devices (MSD), dedicated to the treatment of sewage. On these ships, grey water is typically not treated (EPA, 2008). MSD must be approved by the flag state of the vessel and comply with local effluent standards, if available. EPA (2008) reports that conventional MSD on board cruise ships treat sewage through biological treatment and chlorination, while some systems combine maceration and chlorination. Advanced Wastewater Treatment Systems (AWTS) comprise a range of relatively new technologies for treating sewage more effectively than the older MSD. For these systems to function properly, the influent of sewage is typically not sufficient. Thereto, (part of) the grey water streams are also routed through the AWTS. The use of these systems is becoming the standard in the cruise industry (King County, 2007) and newbuilds are typically fitted with such systems (Nuka Research, 2019). From the 2021 Cruise Report Card, published by Friends of the Earth[6] and covering the 18 major cruise lines and 202 ships, it can be derived that 75% of the cruise ships have an AWTS. According to Vard (2018), most AWTS on board cruise ships are of the Membrane Bioreactor (MBR) type, utilizing an activated sludge process in combination with membrane filtration. Systems of the Moving Bed BioReactor (MBBR) type consist of a bioreactor filled with plastic beads, supporting bacterial growth, in combination with a Dissolved Air Flotation (DAF) unit (Huhta et al., 2007). No complete overview could be retrieved of systems that are in use throughout the industry. However, the Alaska Department of Environmental Conservation annually reports which large cruise ships operated in Alaskan waters and which type of treatment system is used on

[6]https://foe.org/cruise-report-card/

TABLE 6 | Secondary microplastic release mechanisms and sources with relevance to cruise ship wastewater.

Release mechanism	Source group	Sources
Abrasion and weathering during normal use of plastic and synthetic products and textiles	Plastic items	Hotel facilities: outdoor facilities, incl. public spaces, entertainment areas, catering areas; indoor facilities, incl. passenger, crew, entertainment and service facilities, galleys, shops, medical center Ship facilities: outdoor ship facilities, incl. outdoor deck spaces and equipment, safety equipment, ropes; indoor ship facilities, incl. machinery and comfort system areas, control room and bridge, safety system Stores: disposable plastic items (e.g. cups, straws, personal protective equipment) and packaging People: plastic products brought by crew and passengers (e.g. toys, footwear etc.)
	Textiles	Facilities: permanent textiles in hotel and ship facilities (e.g. carpets, curtains, furniture, etc.) Facilities: professional textiles (e.g. towels, sheets etc.) Stores: cleaning cloths People: personal textiles (e.g. clothing, towels, etc.)
Laundry and cleaning of textiles	Textiles	Hotel facilities: professional textiles (e.g. towels, sheets, crew uniforms etc.) People: personal textiles (e.g. clothing, towels, etc.)
Particles released from painted surfaces	Painted surfaces	Hotel facilities: outdoor hotel facilities, incl. sun decks, pool areas, catering areas; indoor hotel facilities, incl. accommodation, hallways, catering areas, entertainment Ship facilities: outdoor ship facilities, incl. decks, superstructures, safety devices, equipment; indoor ship facilities, incl. indoor vessel structure, tanks, machinery spaces, bridge
Dust from the abrasion of turfs and fields	Artificial turfs, sports fields, artificial grass, playgrounds	Facilities: artificial grass (e.g. mini golf) and shock absorbing floors used in e.g. running tracks, sports fields and playgrounds
Waste handling and littering	Solid waste handling and compacting	Stores: (food) packaging materials Stores: single-use plastic items Stores: printed materials People: personal plastic and paper waste
	Food pulper	Stores: (food) packaging materials Stores: single-use plastic items
	Waste incineration	Plastic waste from various sources (stores/people)
	Plastic litter	Stores: (food) packaging materials Stores: single-use plastic items Stores: printed materials People: personal plastic and paper waste

TABLE 7 | Linking cruise ship wastewater streams to pathways and microplastic sources.

Wastewater stream	Sub-streams	Primary MPs types	Secondary MPs types
Sewage	Toilet flushing	Cleaning & maintenance	Plastic waste & litter
	Medical wastewater	Medical	
Grey water	Accommodation	Personal care & cosmetics	Plastic waste & litter
		Cleaning & maintenance	Dust, particles and fibers
	Laundry	Cleaning & maintenance	Textile fibers
	Galley	Cleaning & maintenance	Plastic waste & litter
Oily bilge water	Wash water	Cleaning & maintenance	Plastic waste & litter
	Leaks from machinery		Dust, particles and fibers
	Engine room spills		
	Condensates		
	Deck drainage		

board these ships. **Table 8** provides an overview of the different systems that were used on board the ships that operated in Alaskan waters in 2019 (ADEC, 2019), and indicates the number of ships associated with each system. Further information about these systems was collected from the AWTS brand websites, as well as ship-specific implementations, and added to the table. It follows that 18 out of 24 ships had an MBR type of AWTS, and 14 of these were of the brand Hamworthy. Six vessels operated an MBBR type AWTS of which 5 were of the brand Scanship.

The MBR systems all involve a pre-treatment filtering of the influent to remove coarse solids and prevent blocking of the membranes. The treatment itself involves the biological oxidation through an activated sludge process and ultrafiltration through membranes, where concentrates are generally fed back to the bioreactors and filtered effluents are collected in a permeate tank. The MBBR influents also pass filters to remove coarse solids. In the reactor, biological matter is removed through aerobic biological oxidation, and consequently DAF units separate particulate matter. Finally, the effluents pass polishing filters. All systems utilize UV disinfection to remove pathogens. Where available, mesh sizes of screens and filters are included. Since MBR systems are based on ultrafiltration, the mesh of the membranes is very fine with pore sizes below 100 nm.

Both grey water and sewage could be discharged to the marine environment without treatment. This applies to grey water for ships which do not have AWTS and ships which route only certain grey water streams through AWTS. Furthermore, it is possible that treatment systems are switched off at open sea, resulting in discharges of raw sewage and grey water. In 2021, 25% of the cruise fleet had no AWTS in place and thus discharged untreated grey water to the marine environment. Since these would typically concern older, and smaller cruise ships, the percentage of total grey water discharged through this route is likely smaller and this is expected to decrease in the future due to the increased use of AWTS. The MARPOL Convention allows the discharge of untreated grey water and, under certain conditions, sewage outside coastal zones. So theoretically, treatment systems could be switched off when the ship is on open seas. An EPA survey of four cruise ships fitted with AWTS reports that all vessels operate the system on a continuous basis (EPA, 2006a; EPA, 2006b; EPA, 2006c; EPA, 2006d) and therefore do not discharge raw sewage. This is in line with the CLIA waste management policy, which prohibits the discharge of untreated sewage on board member cruise lines[9]. One of the ships in the EPA survey (EPA, 2006b) only routes the grey water from accommodations to the AWTS and discharges galley and laundry wastewater overboard without treatment, demonstrating that discharges of untreated grey water also occur on vessels with AWTS. AWTS and MSD filtering and treatment processes separate the wastewater into treated effluents and waste products. Sewage is typically high in solids, such as toilet paper and sanitary items, which is removed before sewage enters the treatment system, leaving screening solids of various sizes in the sieves and membranes. Another waste stream is the formation of biosludge. Biosludge or excess biomass consists of organic material as well as bacteria, resulting from the biological consumption of sewage (EPA, 2008) and contains over 95% water (Avellaneda et al., 2011). It is separated from the treated effluents by filtration (EPA, 2008) and therefore would contain any solids such as MPs that have entered the bioreactor.

Literature provides some information on the disposal of waste products from cruise ship sewage and grey water treatment. Disposal options are incineration on board, landing at PRF and discharge at open sea (EPA, 2008; Klein, 2009; Avellaneda et al., 2011). The relevant findings from an EPA survey of four cruise ships with AWTS (EPA, 2006a; EPA, 2006b; EPA, 2006c; EPA, 2006d) are shown in **Table 9**, together with the details of a case study cruise ship, representing an average-sized cruise ship operating in the Caribbean, as described by Kotrikla et al. (2021). From this table it follows that three out of five ships discharge biosludge overboard. One of these ships also discharges the screening solids from the laundry and accommodation wastewater treatment system overboard, whilst solids from sewage are collected and incinerated on board. These data are in line with Klein (2009) who reports the overboard discharge of waste biosludge by 15 out of 16 ships in Washington State waters, with dewatering and incineration of biosludge on board one ship. Experts interviewed as part of this research stated that delivery of biosludge to PRF is currently not a common method on a worldwide scale as adequate facilities are lacking. This is also outlined by Avellaneda et al. (2011) who raise

[7] https://www.wartsila.com/waw/waste-treatment/wastewater/membrane-bioreactors
[8] https://www.environmental-expert.com/products/membrane-bioreactors-mbr-245436
[9] https://cruising.org/en/-/media/Sustain/CLIA_EnvInnovations_FS2019%20FINAL

TABLE 8 | Overview of characteristics of AWTS systems and processes on cruise ships operating in Alaskan waters during 2019.

Brand	No. of ships	Type	Pre-treatment	Main treatment steps	Effluent management	References
Wärtsilä Hamworthy	14	MBR	Aeration of buffer tanks, mixing, screen presses (400 µm)	Two stages of aerated bioreactors, external membrane ultrafiltration (40 nm)	UV disinfection	Wärtsilä[7], EPA (2006d)
Scanship	5	MBBR	Coarse drum filters (0.5mm)	Aerated MBBR bioreactor with addition of defoaming agent, DAF with addition of anionic polymer and flocculant	Polishing screens (0.03 mm), UV disinfection	EPA (2006c)
Zenon ZeeWeed	2	MBR	Mixing, coarse screens	Aerated bioreactors, submerged membrane ultrafiltration	UV disinfection	EPA (2006b); Celebrity (2013)
Hydroxyl CleanSea	1	MBBR	Mixing, fine screen rotating drums	Aerated MBBR bioreactor (no additives), DAF	Tertiary filtration, UV disinfection	Celebrity (2013); Headworks International (2018)
Rochem Bio-filt	1	MBR	Mixing, addition of antifoam chemical, vibratory screen filter (104 µm)	Aerated bioreactors, external membrane ultrafiltration	UV disinfection	EPA (2006a)
Triton Water	1	MBR	Not specified	Aerated bioreactors, submerged membrane ultrafiltration (0.05 µm)	Not specified	Environmental XPERT[8]

the logistic challenges of dealing with the large amounts of biosludge from cruise ships in ports without fixed reception facilities, rendering this scenario unrealistic. The available data indicates that for screening solids, incineration or delivery at PRF is more common.

3.5.2 Oily Bilge Water

As international regulations prohibit the discharge of untreated bilge water, there are two main methods used for the disposal of oily bilge waters: storage on board and delivery to onshore facilities, and onboard treatment. The treatment of bilge water is aimed at separating the oily constituents and water, such that the treated bilge water can be discharged overboard and the oily constituents are retained on board in sludge tanks for delivery to shoreside facilities (EPA, 2011). The systems used for the treatment of oily bilge waters are generally referred to as Oily Water Separators (OWS). EPA (2011) reports that contemporary OWS are comprised of a series of different separation methods and that all of the OWS systems for bilge waters that are approved by the US Coast Guard are a combination of gravity-based separation and one or more forms of polishing treatment. Oil and other contaminants that are contained from the bilge water are collected in sludge tanks. This oily sludge may be stored on board for discharge at shore reception facilities or incineration on board. **Table 10** summarizes representative options for wastewater treatment and the discharge and disposal of the resulting effluents and waste products.

3.6 Cruise Line Questionnaire

Since the questionnaire was distributed almost simultaneous with the first infections of COVID-19 on board cruise ships, the response was minimal. One CLIA member company responded and completed the questionnaire. However, with a fleet size of over 15 vessels, the responding company can be considered an important player in the industry and generally representative.

All ships of this company have holding tanks and MSD or AWTS systems for the treatment of sewage and grey water, with most ships having AWTS. In the case of MSD, grey water is stored on board and discharged at a minimum distance of 12 nautical miles from the nearest land. All ships are equipped with OWS for the treatment of oily bilge water, and also fitted with holding tanks for discharge at PRF when necessary.

All MSD operated by the company are using biological treatment in combination with chlorination. The screening solids captured by the treatment process are incinerated on board. The MSD are operated on a continuous basis. When the ships operate within 12 nautical miles from nearest land, treated effluents are contained in storage tanks and discharged later.

Most AWTS installed are of the MBBR type, and some are MBR. All sewage, accommodation, laundry and dishwashing wastewater streams are routed through the AWTS. The systems are operated on a continuous basis and effluents are discharged at a minimum distance of 3 nautical miles from the nearest land, confirming commitment to the CLIA zero-discharge policy for untreated sewage. Biosludge is either discharged to sea, incinerated or landed at PRF, where the chosen method depends primarily on the region of operation. Screening solids are typically incinerated on board and ashes are delivered to PRF.

TABLE 9 | Sewage sludge treatment and disposal on board four cruise ships (EPA, 2006a) (EPA, 2006b) (EPA, 2006c) (EPA, 2006d).

Ship	Treatment type	Waste streams	Disposal
Oosterdam (EPA, 2006a)	1. Chemical disinfection and reverse osmosis	Coarse screening solids from vibratory screen filters	Incinerated on board
	2. MBR	Spent bag filters from fine bag filters	Shredded and incinerated on board
		Screening solids from vibratory screen filters	Discharged overboard
		Waste biosludge	Discharged overboard
Veendam (EPA, 2006b)	MBR	Screening solids from coarse filters	Shredded and stored in collection tank, disposal ashore
		Waste biosludge from bioreactor	Discharged overboard
Norwegian Star (EPA, 2006c)	MBBR	Coarse drum filter solids	Stored in solids holding tank; dewatered, pressed and dried and incinerated on board; ashes are brought ashore.
		DAF solids (excess biomass from reactors)	
Island Princess (EPA, 2006d)	MBR	Screening solids	Collected in plastic bags which are incinerated on board; ashes are brought ashore
		Spent bag filters from interstage bag filters	Incinerated on board with screening solids
		Waste biosludge	Discharged overboard
Case study ship (Kotrikla et al., 2021)	Biological decomposition and disinfection	Screening solids and biosludge	Disposed in PRF

In terms of policies, the company reports the initiation of the phasing out of "discretionary single use plastics on our ships". Additionally, onboard gift shops and spas do not sell products containing microbeads. No measures were reported regarding the use of synthetic textiles or the application of microfiber filters in laundry installations.

4 DISCUSSION

This article explored for the first time the sources and pathways of MPs in cruise ship wastewater, using a novel approach, based on general literature on MP sources in the marine environment as well as literature and industry information on cruise operations and wastewater management practices on board cruise ships. An overview was presented of the main source groups and release mechanisms of primary and secondary MPs on board cruise ships. Pathways of MPs were identified by linking the identified sources to the main wastewater streams on board cruise ships and an assessment of typical wastewater management practices.

4.1 Inventory of Sources

An overview was presented of the main source groups of primary MPs on board cruise ships, each reflecting the types of products and operations that are relevant to MP releases: personal care & cosmetics, cleaning & maintenance, medical & pharmaceutical and miscellaneous. PCCP are generally considered a key source of MPs in onshore wastewater treatment plants (e.g. Carr et al. 2016; Mason et al. 2016). There is no reason to assume that this would not be the case on board cruise ships. Moreover, the use of sun protection products and presence of spa and beauty facilities could result in even higher loads. Both fragrances and UV-filters linked to PCCP have been detected in cruise ship wastewater (Westhof et al., 2016; Vicente-Cera et al., 2019b), with concentrations of fragrances at similar levels as those in onshore domestic wastewater and concentrations of UV-filters exceeding those (Vicente-Cera et al., 2019b). It should be noted that the data reported in the latter study were collected under maintenance conditions and could be an underestimate for normal operations with passengers on board. This suggests that cruise ship wastewaters contain concentrations of PCCP constituents that are similar or exceeding those of onshore wastewater. Several studies (Sundt et al., 2014; Lassen et al., 2015; Magnusson et al., 2016) assessed medical and pharmaceutical products as a minor source of MPs to the environment. Both Westhof et al. (2016) and Vicente-Cera et al. (2019b) found concentrations of pharmaceutical compounds in cruise ship wastewater at similar levels compared to domestic wastewater, suggesting no substantial differences in their use on board cruise ships and on land.

Literature reports MPs and synthetic polymers in various products used for industrial cleaning and care. These include hard surface cleaners, toilet cleaners and blocks, stainless steel cleaners, bathroom acid cleaners, oven cleaners, laundry detergents and stain removers (Scudo et al., 2017), commercial hand-cleaning products (Lassen et al., 2015; Scudo et al., 2017) and synthetic waxes in floor

TABLE 10 | Summary of identified representative wastewater management options per wastewater stream.

Wastewater streams	Treatment	Subtype	Liquid effluents	Discharge of effluents	Waste products	Disposal of waste products
Sewage	No treatment	–	Untreated sewage	Disposal at PRF	–	–
				Overboard discharge	–	–
	MSD	Biological and chlorination	Disinfected effluent	Overboard discharge	Waste biosludge	Incinerator/PRF/overboard discharge
	AWTS	MBR	Disinfected effluent	Overboard discharge	Screening solids	Incinerator/PRF/overboard discharge
					Waste biosludge	Incinerator/PRF/overboard discharge
		MBBR	Disinfected effluent	Overboard discharge	Screening solids	Incinerator/PRF/overboard discharge
					DAF sludge	Incinerator/PRF/overboard discharge
Grey water	No treatment	–	Untreated grey water	Overboard discharge	–	–
	AWTS	MBR	Disinfected effluent	Overboard discharge	Screening solids	Incinerator/PRF/overboard discharge
					Waste biosludge	Incinerator/PRF/overboard discharge
		MBBR	Disinfected effluent	Overboard discharge	Screening solids	Incinerator/PRF/overboard discharge
					DAF sludge	Incinerator/PRF/overboard discharge
Oily bilge water	No treatment	–	Untreated bilge water	Disposal at PRF	–	–
	OWS	–	De-oiled effluent	Overboard discharge	Oily sludge	PRF

agents (Essen et al., 2015). Most of the listed product types could be relevant to cruise ships. However, no studies could be identified that address concentrations of detergents and other maintenance products in cruise ship wastewater, nor about the presence of MPs in products used for specific ship operations. Scudo et al. (2017) estimated that industrial hand-cleaning soaps used for the removal of grease, paints etc. account for more than half the tonnage of all applications of MPs in rinse-off products. Considering the nature of cruise ship operations, this could be an important source as well. In addition, considering the wide range of applications of MPs in industrial cleaning products, the use of MPs in specialty maritime and cruise cleaning and maintenance products cannot be ruled out.

The identified release mechanisms for secondary MPs include laundry, waste handling and littering as well as the general wear and tear of products, painted surfaces and other surfaces and facilities. The source products encompass a broad array of products and materials. Many of these concern facilities such as painted surfaces, furnishing and safety equipment, but also stores, e.g. disposable plastics, cleaning cloths and packaging materials and personal belongings. Whereas primary MPs in many cases are intentionally released directly to water during product use (Boucher and Friot, 2017), secondary MPs mainly concern unintentional losses. These MPs may end up in wastewater, e.g. through wet cleaning, but could also be disposed of in solid waste or transported off the ship via air. As a result, not all MP sources may be equally relevant to wastewater. Laundry is an exception, as most of the microfibers released during laundry would be drained with laundry effluents to the grey water system. Synthetic textiles are considered a major source of MPs in the marine environment (Carney Almroth., et al., 2018). Azizi et al. (2022) have summarized the findings of over 400 studies about MPs evaluation in conventional wastewater treatment plants on land. The authors concluded that, throughout the plants evaluated in these studies, fibers were most commonly found, with an average abundance of 57% fibers throughout the different treatment steps. The high contribution of fibers is commonly attributed to the washing of synthetic textiles (e.g. Browne et al., 2011; Napper and Thompson, 2016; Ziajahromi et al., 2017; Raju et al., 2018). Cruise ships have extensive laundry facilities for the washing, drying and folding of professional textiles and most ships also offer laundry services for guests and have launderettes for crew. On the Oasis of the Seas about 42,000 kg of laundry is processed on embarkation day[10]. This suggests that laundry may be a major source of MPs on board cruise ships, depending on the nature of professional textiles such as sheets, towels and crew uniforms. To which extent these MPs reach the grey water system also depends on the use of laundry filters, which could remove up to 78% of fibers (Napper et al., 2020) and, as such, could substantially lower the concentration of microfibers in grey water. Many cruise lines have a policy in place, or have pledged to do so, to phase out certain single use plastics such as straws, stirrers and cups[11,12,13,14], to reduce their plastic footprint. In line with this

[10]https://www.theshipyardblog.com/single-post/2018/08/28/How-Cruise-Ships-Work-Part-2-Laundry-Housekeeping-and-Kitchens

trend, cruise lines could consider the use of plastic-free or non-synthetic alternatives for the MP sources that are reported in this study. The majority of the primary MP sources relate to "stores", indicating that these products are purchased on a regular basis by the cruise line. The company that was consulted in this study already stopped the sale of products containing microbeads in onboard shops. Such a policy could be further extended to also cover PCCP that are used throughout the ship (e.g. in bathrooms and spas) as well as cleaning & maintenance products, including industrial hand soaps. Secondary sources of MPs are more varied and also include permanent ship and hotel facilities, for which plastic-free alternatives are either unfeasible or excessively expensive. However, considering that laundry potentially is a major source of MPs in wastewater, measures addressing this specific source could be effective in order to minimize the total MP load in untreated wastewaters, for instance through replacing synthetic textiles with natural alternatives or the use of microfiber filters in laundry systems.

4.2 Pathways Through Wastewater

The results demonstrate that the MP sources attributed to the different wastewater streams vary significantly. The main sources related to sewage are pharmaceuticals, detergents and the disposal of larger plastic items in toilets. The sources related to grey water include PCCP, detergents, fibers from synthetic textiles and secondary MPs that are removed by wet cleaning. The sources attributed to oily bilge water mainly relate to engine room operations. The findings for sewage and grey water are in line with the findings of Westhof et al. (2016), who evaluated the presence of different types of micropollutants in various wastewater streams on board a cruise ship. Their findings reveal a predominance of oral pharmaceutical residues in sewage with lower concentrations of other pollutants attributed to human excretion. In grey water the highest concentrations were found for caffeine, attributed to the draining of remaining coffee and residues to the grey water system, and flame retardants, which according to the authors diffused from the host material and were consequently discharged to wastewater via laundry, handwashing, bathing and showers. In addition, significant concentrations of pharmaceuticals, UV filters, fragrances and a plastic softener were found, indicating the relevance of PCCP, skin applied pharmaceuticals (e.g. salves) and laundry detergents for grey water.

This paper focused on MPs in the main wastewater streams on board cruise ships. Miscellaneous wastewater streams include ballast water, wastewater from pools, whirlpools and spas, food pulper effluents, effluents from sinks and drains, deck wash water and runoff, wash water from exhaust gas cleaning systems, cooling water, condensates as well as various types of operational wastewater from different types of equipment and machinery (EPA, 2008; EPA, 2013; MEPC, 2017). These could also act as significant pathways of MPs. Ballast waters, for instance, have been reported to contain very high concentrations of MPs (Matiddi et al., 2017). In order to assess the total contribution of MP pollution from cruise ship wastewater, these pathways should also be considered.

4.3 Wastewater Management

MPs in cruise ship wastewater may be discharged to the ocean through the discharge of both untreated and treated effluents, as well as through the overboard discharge of waste products from wastewater treatment.

The performance of wastewater treatment systems that are in use in the industry is not well documented due to a lack of administrative monitoring (Westhof et al., 2016) and their effectiveness in retaining MPs in particular has not been comprehensively documented. EPA (2008) reports various pollutant concentrations in the effluents from various sampling efforts of AWTS and MSD effluents of cruise ships operating in USA waters between 2003 and 2005, with non-detected values for both settleable and suspended solids in most AWTS effluents. This indicates that the cruise ship AWTS included in the sampling efforts were generally effective in capturing solids. Furthermore, both membrane ultrafiltration, a main component of MBR systems, and DAF, a main component of MBBR systems, are associated with very high MP removal rates in onshore systems. For MBR and membrane ultrafiltration, rates reported in literature (Talvitie et al., 2017a; Lares et al., 2018; Ma et al., 2018; Lv et al., 2019) exceed 99% and this is considered the most effective technology to remove MPs in onshore WWTP (e.g. Sun et al., 2019). For DAF, values between 70% and 96% are reported (Talvitie et al., 2017a; Esfandiari and Mowla, 2021), for different types of flocculants and coagulants that are added during the process. On the other hand, EPA (2008) reports values of suspended solids in the effluents of cruise ship MSD systems which are substantially higher than the USA discharge standards for onshore wastewater treatment systems, indicating that these systems may be less effective in capturing MPs. No data could be retrieved regarding the effectiveness of OWS in capturing particulate matter. Onshore wastewater treatment plants are generally considered important sources of MPs in aquatic environment, despite their effectiveness in removing MPs from influents, due to the large volumes of wastewater that pass these plants [e.g. Talvitie et al. (2017b)]. Considering the volumes of wastewater that are generated on board cruise ships, treated wastewater from cruise ships therefore represents a significant pathway.

The results of this study reveal that, currently, 25% of the world cruise fleet discharges all grey water without treatment to the ocean as these ships do not have AWTS. In addition, AWTS configurations not necessarily cover all grey water sub-streams and as a result, a potentially significant volume of grey water is discharged without treatment from ships with AWTS. Further study of typical configurations is required to assess the volumes and characteristics of such discharges throughout the industry.

Various studies of onshore wastewater treatment plants have investigated the fate of MPs in onshore wastewater treatment plants, demonstrating that the vast majority of MPs in the influent are captured in sludge (Carr et al., 2016; Talvitie et al.,

[11] https://presscenter.rclcorporate.com/press-release/18/royal-caribbean-to-eliminate-plastic-straws-by-end-of-2018/

[12] https://www.maritime-executive.com/article/carnival-targets-single-use-plastics

[13] https://www.cruiseindustrynews.com/cruise-news/24042-msc-cruises-signs-single-use-plastic-charter.html

[14] https://www.ncl.com/travel-blog/norwegian-eliminates-single-use-plastic-bottles

2017b; Gies et al., 2018). Since sewage sludge is commonly recycled as fertilizer in agriculture applications (Nizzetto et al., 2016), this represents a major pathway of MPs to the environment on land, leading to the accumulation of MPs in agricultural soils (Corradini et al., 2019). Similarly, biosludge resulting from AWTS treatment on board cruise ships likely contains high concentrations of MPs, due to the expected effectiveness of MBR and DAF in capturing MPs. The results of this paper indicate that while three options for the disposal for biosludge are used throughout the industry, overboard discharge is the most common method. The overboard discharge of this substance therefore leads to a delayed and concentrated discharge of the MPs in grey water and sewage and this practice should be avoided. The development of adequate PRF for biosludge in cruise regions could be instrumental in reducing the volumes of MPs that are discharged through this pathway, especially in vulnerable areas receiving large numbers of cruise ships. The literature review as well as questionnaire response indicates that overboard discharge of screening solids is not common, however this practice has been reported for one ship by EPA (2006a), indicating that this scenario cannot be ruled out.

In general, the available literature on wastewater treatment systems is restricted to a small number of dated reports (e.g. King County (2007); Huhta et al. (2007); EPA (2008); EPA (2011), most of which were produced by USA government authorities. Furthermore, the available data regarding the practices of discharging untreated grey water and sewage as well as the overboard discharge of biosludge concern a limited number of isolated and largely dated case studies (e.g. EPA, 2006a; EPA, 2006b; EPA, 2006c; EPA, 2006d; Klein, 2009; Kotrikla et al., 2021). In order to address these knowledge gaps, this research collected information on both wastewater treatment systems and wastewater management practices from one large cruise line. The results confirm trends and practices in wastewater management as reported by other studies (see section 3.5.1). However, it should be noted that these efforts either build on voluntary contributions or on cruise operations in the USA, and Alaska in particular; an area that is more strictly regulated and monitored than the mainstream cruise regions in the Caribbean and Mediterranean. Therefore, these results are likely biased and caution should be taken when extrapolating these results to the industry as a whole, in particular in vulnerable areas with little regulation and/or inadequate enforcement. An industry-wide overview of wastewater management systems and practices, ideally linked to regions of operation, would greatly support the understanding of leakages of MPs and other pollutants from cruise ship wastewater.

Finally, as recently raised on one of the leading digital platforms in the maritime industry[15], the improper management of solids in sewage may lead to discharges through other pathways, such as the disposal of any solids remaining in the holding tanks and the use of cutter pumps in the collection and treatment of sewage. These cutter pumps are purposely designed to remove the load on screens by breaking down solids in smaller particles. This is rendering screenings less effective, and even contributing to the formation and release of MPs to the environment. This further emphasizes the need for a holistic approach of wastewater management in order to prevent leakages of MPs.

[15] https://www.maritime-executive.com/editorials/ships-discharge-10-000-cubic-meters-of-plastic-a-year-from-sewage

4.4 Conclusions

This paper for the first time explored the sources and pathways of MPs in cruise ship wastewater, providing insight on the array of sources and pathways, highlighting priority areas for mitigation and identifying additional knowledge gaps. On the level of individual companies or ships, the overview of sources and pathways allows for the identification of mitigating measures from source-to-sea, by identifying the full array of sources and mechanisms that contribute to the release of MPs to wastewater, as well as the connections between sources and the different wastewater streams. As a result, it also provides guidance for purchasing policies by cruise lines and the need for ongoing education of crew and passengers.

In general, it is recommended that cruise lines consider the inclusion of PCCP well as cleaning and maintenance products containing primary MPs in their policies to phase out the use of single-use plastics. In addition, the replacement of professional synthetic textiles with non-synthetic alternatives and the use of laundry filters could be effective in reducing the MP load in wastewaters. Furthermore, adequate wastewater management is key to prevent MP leakages and reduce the MP load in wastewaters that are discharged to the ocean. This is greatly supported by the increased use of AWTS. However, the use of these systems is only a partial solution, which should be part of a holistic management of wastewater streams. Efforts should be made to minimize discharges through waste products, wastewater streams bypassing AWTS as well as wastewater streams other than discussed in this study. Although at the global scale, the quantitative contribution of MPs from cruise ship wastewater is small in comparison to land-based sources, local impacts could still be significant due to the large amounts of wastewater, waste products that are discharged without treatment, the vulnerability of the exposed coastal and marine ecosystems and the concentrated nature of cruise activities. To better place the problem in perspective, identify cost-effective measures and areas at risk, it is required that MP concentrations in different effluents and waste products are quantified through measurements and that contemporary wastewater management systems and practices throughout the industry are better understood.

In conclusion, the approach for this study was successful in exploring the major sources and pathways of MPs within the study scope, and to highlight knowledge gaps and starting points for mitigation. This makes it a valuable tool that could also be applied in other maritime sectors and will support global efforts to identify all sources and pathways of MPs within the context of the UNEA-5.2 resolution.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

The research was performed by MF and she also wrote the paper. CC and AL contributed by guiding the research, discussing ideas and supervising the writing of this paper. All authors contributed to the article and approved the submitted version.

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