Chapter

Management of Nutrient-Rich Wastes and Wastewaters on Board of Ships

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Abstract

Ship-generated nutrient-rich waste sources, including food waste and sewage water, contribute to eutrophication and deoxygenation of marine ecosystems. This chapter aims to discuss the characteristics of these waste and wastewater sources, review current ship-generated organic waste and wastewater regulations, inventory conventional management and treatment practices, and identify future perspectives for more sustainable nutrient-rich waste and wastewater management on board of ships. According to regulations, untreated food waste and sewage can generally be discharged into the open sea at more than 12 nautical miles from the nearest land, hence this is currently a common practice. However, special restrictions apply in special designated areas such as the Baltic Sea, where food waste must be comminuted/grounded and nutrients need to be removed from the sewage prior to discharge at 12 nautical miles from the nearest land. Current research looks at the valorisation of these waste and wastewater sources through anaerobic digestion, composting and/or nutrient recovery.

Keywords: food waste, management, maritime, nutrients, organics, sewage, ship, valorisation

1. Introduction

Nutrients such as nitrogen and phosphorus can cause devastating impacts on the aquatic environment. Although nutrient pollution in rivers and lakes has been widely studied and measures have been put in place to reduce nutrient discharge in these environments [1, 2], much less attention has been paid to nutrient pollution in marine ecosystems. Nutrients can enter seas and oceans through discharge of wastewater and food waste generated either at land or on board of ships, aquaculture practices or fertilizer run-off from agricultural land [3]. Such excessive nutrient discharges into the marine environment, combined with ocean warming due to climate change has resulted in ocean deoxygenation [3, 4]. Globally, the oxygen content of the ocean has decreased by around 2% since the middle of the 20th century [4]. This number is expected to further decrease by 3 to 4% by the year 2100 under a business-as-usual scenario [4]. Much of the oxygen loss occurs in the upper 1000 m where species richness and abundance is the highest [4, 5]. Sensitive species are as such replaced by more tolerant and resilient species, with a decrease of biological diversity as a result [3]. Ocean warming-induced deoxygenation is driven by the fact that warmer ocean water caused by climate change holds less oxygen and is more buoyant than cooler water [5]. This leads to reduced mixing of oxygenated water near the surface with deeper waters, the latter naturally containing less oxygen [5]. Warmer water also raises the oxygen demand from living organisms. As a result, less oxygen is available for marine life [3, 4]. Nutrient-induced deoxygenation is caused by the abundance of nutrients that induce eutrophication, a phenomenon often found in coastal waters [6]. Eutrophication is characterized by the production of harmful algal blooms and may result in oxygen depletion of the water body after the bacterial degradation of the algae [6]. Moreover, certain species of algae produce biotoxins, which are natural poisons that can be transferred through the food web, potentially harming higher-order consumers such as marine mammals and humans [6, 7]. If human-accelerated eutrophication is not reversed, the entire coastal ecosystem may ultimately be devastated.

The significant growth of the maritime transportation sector over the last decade has accelerated the devastating environmental impact on marine ecosystems [8, 9]. The cruise ship industry now transports about 22 million people annually around the world [10]. Moreover, marine policy stimulates transport of cargo by sea, thereby also further increasing the number of people (staff) traveling over sea [10, 11]. This increase in maritime transportation comes with a global increasing amount of ship-generated waste. Nutrient-rich waste on board of ships includes sewage (gray and black wastewater), as well as food waste [9]. Despite the increasing knowledge and concern of the environmental impact of nutrient discharges into the marine environment, these organic waste sources are often still dumped into the open sea without treatment [12]. As an example, ship-generated nutrient discharge into the Baltic Sea has been estimated at 269 tons of nitrogen and 256 tons of phosphorus in the year 2000 [12]. Since ship-generated waste pollution is one of the main concerns of this area, it has been declared as a Particularly Sensitive Sea Area by the International Maritime Organization (IMO) [13]. This means that the area now requires special protection through legislation and actions because of its socioeconomic and scientific importance [13, 14].

This chapter discusses the source of nutrient-rich wastes and wastewaters produced on board of ships, current ship-generated organic waste and wastewater regulations, management and treatment practices, as well as future perspectives for more sustainable nutrient-rich waste management on board of ships. As such, this chapter may point out opportunities to reverse human-accelerated eutrophication of marine ecosystems.

2. Sources of nutrient-rich wastes and wastewaters on board of ships

2.1 Food waste

The international maritime organization (IMO) defines ship-generated food waste as spoiled or unspoiled food substances containing fruits, vegetables, dairy products, meat products, and food scraps [14]. Large vessels (cargo and cruise ships) generally classify these residues into soft organic food waste (ex. peels and leftovers) and hard organic food waste (ex. bones), as well as packaging [15]. The quantity and composition of ship-generated food waste depends on a variety of parameters such as the ship type, the sorting strategy, the geographical area, the choice of the menu, etc. Cruise ships typically create the highest amount of food waste, with values up to 3.5 kg/person/day [8]. This waste type has an average dry weight (DW) and organic carbon content in the range of 22–38% and 46–60%, respectively, and an average nitrogen and phosphorus content in the range of

8.4–43 g/kg DW and 4.2–8 g/kg DW, respectively [16]. The management of food waste is a major concern on ships since the wet material is subject to fast degradation with odor pollution as a result. Hence, proper and efficient waste management strategies must be put in place.

2.2 Sewage

As for land-based wastewaters, ship-generated wastewaters are generally classified into black and gray water. Black water is sewage generated by toilets and medical facilities, while gray water is generated by showers, washing machines, and dish washers. Sewage on ships is generally more concentrated (about 2–3 times) than its land-based equivalent due to water-saving measures on board [12]. Studies Butt [17] and Svaetichin [18] estimated the volume of wastewater generated by cruise ships (2000–3000 passengers) in the range of 550–800 m^3/day of gray water and 110–115 m^3/day of black water. The release of nutrients into ship-generated sewage water is estimated at 12–15 g/person/day for nitrogen and 3–5 g/person/day for phosphorus [12, 19]. These nutrients that are responsible for eutrophication constitute a large proportion of the sewage water, hence to avoid harmful environmental impacts sewage should be properly stored and/or treated.

3. Ship-generated waste regulations

Ship-generated waste discharge is regulated by the MARPOL convention, i.e. the International Convention for the Prevention of Pollution from Ships adopted in 1973 by the IMO specialized agency of the United Nations and the global regulator of shipping [20]. According to Annex V of [21], food waste is an organic material categorized as garbage. An important feature of the Annex is the complete ban imposed on the disposal into the sea of all forms of plastics. For food waste itself, discharge following comminution or grounding of the residues is generally permitted at a distance of more than three nautical miles from the nearest land. However, in special designated areas such as the Baltic Sea, a distance of more than 12 nautical miles from the nearest land must be respected [22]. Discharge of not comminuted or grounded food waste is prohibited in special areas, but is allowed outside special areas at a distance of more than 12 nautical miles from the nearest land [22]. Ships are also allowed to shred and store their food waste on board for delivery at port reception facilities (PRFs) where it could potentially be collected and valorised. However, for ships that travel internationally, the food waste is classified as international waste and must therefore be eliminated. In the European Union for example, international food waste is considered as " high-risk category 1 animal by-products " [23, 24].

Sewage water discharge is regulated according to MARPOL Annex IV [25]. Ship-generated black water can generally, i.e. in non-special areas, be directly released into the open sea at a distance of 12 nautical miles from the nearest land. Sewage that is comminuted and disinfected using an approved system can be discharged into the sea at a distance of three nautical miles from the nearest land. General sewage water effluent standards prior to discharge into the sea are provided in **Table 1**. In special areas such as the Baltic Sea, additional sewage discharge restrictions apply. As such, for cruise ships operating in special areas, special limitations for nitrogen and phosphorus discharge have recently been established: maximum effluent concentrations of 20 mg/L (or 70% reduction) for nitrogen and 1 mg/L (or 80% reduction) for phosphorus. There are also voluntary initiatives in the shipping industry. As such, the European Cruise Council implemented the Agreement on

	Fecal coliforms (/100 mL)	Suspended solids (mg/L)	pH	Biochemical oxygen demand (BOD5, mg/L)	Chemical oxygen demand (COD, mg/L)
Treatment plant installed before 1/1/2010	250	50 if tested ashore (100 if tested on-board)	—	50	—
Treatment plant installed after 1/1/2010	100	35	6–8.5	25	125

Table 1.
Sewage water effluent standards prior to discharge into the sea at more than 3 nautical miles from the nearest land (MARPOL, Annex IV) [25].

	Food waste	Sewage water
General	Food waste can be comminuted/grounded and discharged into the sea at least 3 nautical miles from the nearest land if the ship is en route. Discharge of not comminuted or grounded food waste is allowed at a distance of more than 12 nautical miles from the nearest land if the ship is en route. Delivery of comminuted food waste to port reception facilities is allowed. Discharge of plastics is not allowed.	Sewage discharge into the sea is prohibited except if the ship has an approved sewage treatment plant or in the case that the ship discharges comminuted and disinfected sewage using an approved system at a distance of more than 3 nautical miles from the nearest land. Not comminuted or disinfected sewage needs to be discharged at a distance of more than 12 nautical miles from the nearest land when the ship is en route and proceeding at not less than 4 knots, and the rate of discharge should be approved.
Special area	Food waste can be comminuted/grounded and discharged at least 12 nautical miles from the nearest land. Delivery of comminuted food waste to port reception facilities is allowed.	From 2019 on, all new passenger ships must either treat nitrogen and phosphorus in black water or leave black water at port reception facilities for treatment in wastewater purification systems. Untreated black water cannot be pumped into the ocean. There are no special limitations for gray water.

Table 2.
Simplified overview of MARPOL regulations regarding food waste, black water and gray water for passenger ships [21, 22, 25].

Discharges in the Baltic Sea. This agreement declares that its members will stop releasing wastewater into the Baltic Sea and instead deliver it to port reception facilities without a special fee. Further, it must be remarked that wastewater treatment still generates a concentrated residual product, i.e. the sewage sludge, which also needs to be treated or delivered to port reception facilities [12].

A simplified summary of the MARPOL regulations applicable to organic waste sources is provided in **Table 2**.

4. Management and treatment practices

The management of ship-generated food waste is typically specific to ship policy. Direct discharge of food waste into the sea following grinding or comminution is for sure the cheapest and most straightforward method. However, since this practice is associated with environmental issues, discharge is not always possible according to regulations (**Table 2**). Moreover, some ship owners prefer to opt for more sustainable solutions on a voluntary basis. Alternative food waste management strategies currently applied include comminution, shredding or grinding of the waste source on board, followed by collection in bins and delivery to port reception facilities for disposal or further treatment. However, storage of food waste on board is challenging for multiple reasons: 1) It can carry diseases or pests and hence needs to be stored in covered containers, 2) It can involve large volumes with risk of putrefaction and odors, hence drying of food waste is recommended, as well as storage in a cooled room, 3) Larger ships should distinguish between soft and hard organic waste for separate storage and treatment; The hard organic waste and packaging is generally stored in bags or bins and delivered to port reception facilities. 4) International food waste needs to be handled differently from domestic food waste because of the risk of spreading diseases [8]. An overview of current common ship-generated food waste management practices is provided in **Figure 1**.

Ship-generated sewage needs to be treated onboard prior to discharge at more than 3 nautical miles in order to respect the regulations provided in **Table 1** or delivered to port reception facilities. In the latter case, the sewage is collected in a storage tank on board and chemicals are added for odor and color removal, as well as disinfection, prior to delivery to the reception facility. Sewage storage strategies vary depending on the type of ship; some vessels store both black and gray water in the same tank. However, storing onboard is associated with difficulties such as limited storage space, next to odor and pest control, so ships need to go to land at regular intervals if direct release of wastewater into the sea is not possible [8, 26].

Most large ships (cargo and cruise ships) have an approved treatment system onboard allowing them to discharge the wastewater into the sea following proper treatment. In a first stage, a pre-treatment such as screening to remove grit and debris is typically applied. Next, an aerobic biological treatment step (activated sludge) is generally applied to remove solids, biological oxygen demand (BOD5) and some nitrogen. Finally, a disinfection step is applied, typically using chlorine. A simplified schematic overview of the conventional treatment process is provided in **Figure 2**.

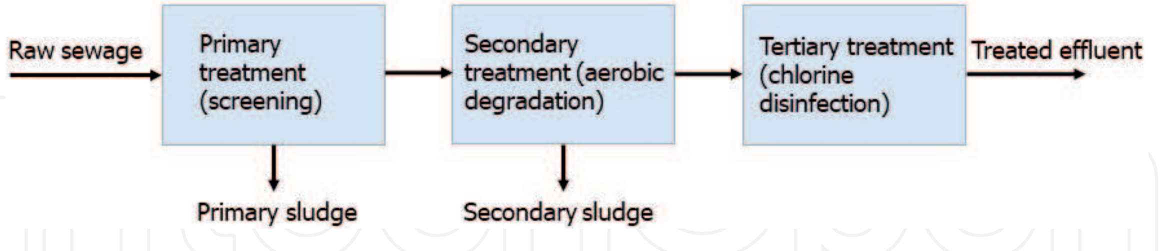

Figure 1.
Overview of common ship-generated food waste management practices. The dotted line indicates a common practice that is prohibited in special areas. NM: Nautical miles.

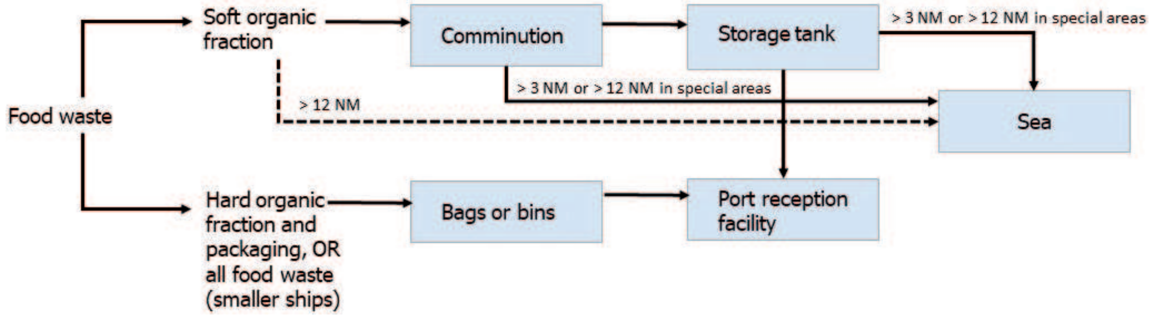

Figure 2.
Conventional on-board treatment process for ship-generated sewage on large ships adapted from 8, 15.

More advanced wastewater treatment systems are also applied involving improved screening, biological treatment (e.g. using membrane bioreactors), solids separation (e.g. using filtration and flotation) and disinfection (e.g. using ultraviolet light) [27]. The conventional wastewater treatment systems target the removal of suspended solids, BOD5 and pathogens, but typically only remove 58–74% of ammonia and 41–98% of phosphorus [26]. With the new regulations on nutrient discharges (nitrogen and phosphorus) in special areas, a variety of more advanced systems have been proposed to remove these nutrients down to the new discharge levels (**Table 2**). According to Helcom [11], there are currently 52 different wastewater purification systems on the market that meet these special area requirements.

5. Perspectives

While food waste and sewage sludge are often still discharged into the sea, these resources could potentially be valorised in a sustainable way. The study of [28] presents potential valorisation scenarios for domestic ship-generated organic wastes. Five different scenarios were proposed in this study including: 1) Composting on board of the ship, 2) Centralized composting, 3) Composting at the port, 4) Centralized anaerobic digestion, and 5) Anaerobic digestion at the port. Composting involves the aerobic degradation of organic waste in the presence of oxygen to produce an organic soil amendment (the compost). Anaerobic digestion involves the anaerobic degradation of organic waste to produce biogas (bioenergy) and biofertilizer (digestate). These ship-generated organic waste valorisation scenarios were compared in terms of their advantages and disadvantages, the required equipment, and associated costs and revenues [28]. The study concluded that the optimal scenario will depend on 1) the amount of organic waste produced by ships and available at the port, 2) the proximity of an existing centralized treatment plant, and 3) the potential market value and opportunities for composts and digestates produced in the area.

In order to facilitate case-specific decision-making, a decision-support software tool for optimal selection of organic waste management strategies is under development by the first author's research team in close collaboration with experts in geomatics and Quebec industry (www.optim-o.com). The software tool combines a multidimensional database, mathematical models, and a geographical information system to facilitate the development and selection of optimal scenarios. The scope includes the generation and collection of organic waste, the treatment of the waste

Figure 3.
Scope of the optim-O decision-support software tool for optimization of organic waste valorisation chains. Technical, spatiotemporal, environmental, economic, legal and social aspects of waste valorisation are taken into account. Images can be reused under the creative commons license agreement.

through biomethanation, composting and/or nutrient recovery, and the distribution of the end-products such as biogas, digestate, compost and recovered mineral fertilizers (**Figure 3**). As such, the entire valorisation chain can be optimized, taking into account environmental (e.g. greenhouse gas emissions), economic (e.g. operating costs), technical (e.g. process operational conditions), legal (e.g. fertilizer application restrictions), social (e.g. traffic nuisance) and spatiotemporal (e.g. transport distance and route) aspects. Although the tool was initially developed for land-generated organic waste management, future research will look at applications in the maritime sector.

Anaerobic digestion may offer a valuable solution for the valorisation of international organic waste, which is currently eliminated as required by regulation. International waste could be treated in a separate digestion unit at the port, or a small-scale system could be installed on the ship. In this way, the biogas produced from this international waste source could be valorized, while the residual digestate could be disposed of if valorisation would not be possible according to international waste regulations. This perspective will be further explored with the Canadian food inspection agency in the near future.

Finally, conventional wastewater treatment systems on board of ships target the removal of solids and pathogens, and some newer systems also target the removal of nitrogen and phosphorus. Future work will look at the recovery of these valuable nutrients as concentrated fertilizers products or other bioproducts instead of their removal [29]. Strategies such as nitrogen stripping-scrubbing to produce ammonium sulfate liquid fertilizer solution [29], the precipitation of struvite ($MgNH_4PO_4{:}6H_2O$) fertilizer [29] or the application of hybrid anion exchange nanotechnology for phosphorus recovery [30] could provide valuable solutions. An integrated process for nutrient recovery on board of ships will be aspect of research by the first author's research team. As such, sustainability in the maritime sector can be further be improved.

6. Conclusions

Ship-generated nutrient-rich wastes and wastewaters have detrimental impacts on marine ecosystems through eutrophication and ocean deoxygenation. Food waste is currently often discharged into the open sea without any treatment at more than 12 nautical miles from the nearest land. Sewage water can also be discharged into the sea without any treatment at more than 12 nautical miles. However, treatment (solids removal + disinfection) is required for discharge between 3 and 12 nautical miles from the nearest land. Large ships typically have an approved sewage treatment system on board. In special areas, untreated sewage water cannot be discharged into the ocean, and special discharge limits apply for nitrogen and phosphorus. Hence, in recent years, more advanced treatment systems for nutrient removal on board of ships have been proposed. Both food waste and sewage can also be stored on board and delivered to port reception facilities for disposal or treatment. Future research will look at the valorisation of these waste and wastewater sources through composting, anaerobic digestion and/or nutrient recovery in order to further improve sustainable resource management in the maritime sector.

Acknowledgements

The first author is funded by the Natural Science and Engineering Research Council of Canada through the award of an NSERC Discovery Grant

(RGPIN-2017-04838). Céline Vaneeckhaute holds the Canada Research Chair in Resource Recovery and Bioproducts Engineering.

Conflict of interest

The author declares no conflict of interest.

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