

Article

Nutrient Analysis of Food Waste from Ships' Greywater in the Baltic Sea

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Abstract: This case study presents the results of assessments of the potential risk of pollution by food waste in different applied shipping scenarios. A four-step model was used to analyse the applied procedures. The first step of the study involved the identification of possible strategies for on-board food waste management. In the second step, physicochemical tests of visually selected greywater detected high contents of nutrients ($N_{\text{Total}} \leq 238 \text{ mg}\cdot\text{L}^{-1}$ and $P_{\text{Total}} \leq 71 \text{ mg}\cdot\text{L}^{-1}$). Daily nutrient content (DNC) calculations of different food waste management scenarios allowed us to estimate the highest emission value from the discharge of greywater mixed with shredded food waste in the third step. In the final stage of the study, the results obtained made it possible to qualitatively assess the impact of DNC load on food waste management methods in the Baltic Sea environment. This study highlights the potential risk of polluting the Baltic Sea with nutrients and other contaminants in various scenarios, which will impact the marine recovery process. The presented research helps to outline waste management approaches for the reduction of these risks.

Keywords: greywater; food waste; nutrients; pollution; ship emissions; Baltic Sea; waste management



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1. Introduction

Sailors have been using the Baltic Sea for the last few centuries to connect closer and more distant areas with the help of marine transport. As a result, traffic density in the Baltic Sea area involves a wide range of vessels in regional segments, as demonstrated in Figure 1.

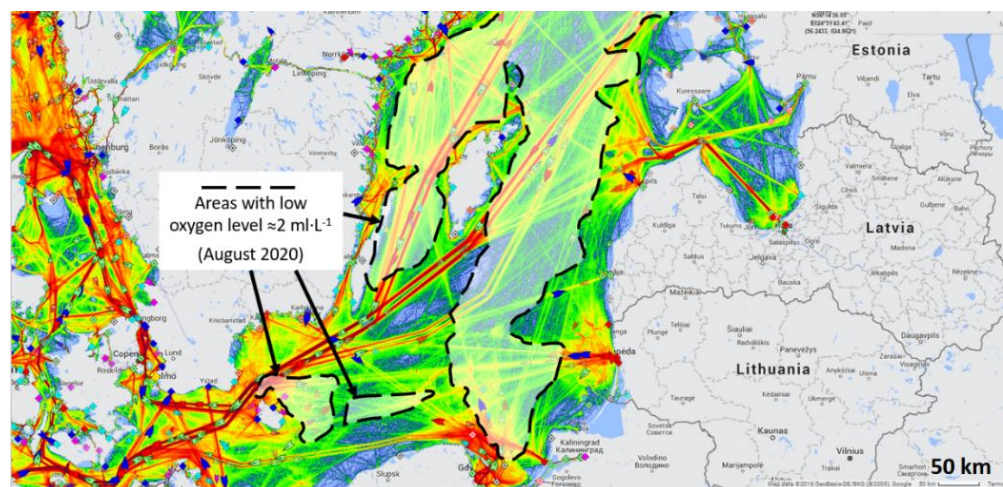


Figure 1. Ship traffic density map of Baltic Sea AIS, 2021, showing transport link development and availability [1] combined with marks indicating the areas with the lowest oxygen content ($\approx 2 \text{ mL}\cdot\text{L}^{-1}$) near the seabed in the open sea [2]. Red lines demonstrate the highest traffic intensities.

Moreover, in recent decades, shipping intensity in the Baltic Sea has increased steadily, which has created persistent environmental problems in combination with the geographical characteristics of the sea. Governing organizations have developed many simple, self-imposed practical and behavioural measures for sewage, garbage/debris, hydrocarbons residuals, greenhouse gas emissions, antifouling agents, physical disturbance of habitats and fauna, and many other impacting factors. The implementation of these measures by boating and shipping operators can minimize environmental impacts resulting from how they operate vessels. However, the lack of information and monitoring has contributed to the continuation of the pollution of the aquatic environment by direct discharges from ships and their crews [3].

The IMO declared the Baltic Sea a “special area” in Annexes I, IV, V, and VI of the International Convention for the Prevention of Pollution from Ships in 1973, which was amended by the 1978 Protocol (MARPOL 73/78) to strengthen legal requirements for the environment protection in subjected areas. About four decades later (in 2011 [4]), the Baltic Sea was declared the first “special area” in Annex IV of MARPOL in order to prevent pollution by sewage and, therefore, minimize the eutrophication in this region [5]. According to Annex IV, the term “ship sewage” includes both “black water” and “greywater”. The designation “black water” relates to sewage and other waste from toilets of any kind (including medical and animal housing), urinals, and water closets or other effluents mixed with the above. On the other hand, so-called “greywater” consists of drains from washbasins, galley sinks, showers, laundries, baths, and washbasin drain but does not include “black water” [5]. However, Annex IV does not apply any regulation to the composition of greywater. As a result, researchers are worried about legal discharge of mixtures of greywater and food waste into the Baltic Sea from ships.

Annex IV imposes stricter requirements for passenger ships sailing in the Baltic Sea. Sewage treatment plants must be used before discharging treated effluents into the sea by new passenger ships from 1 June 2019 and by existing ships from 1 June 2021 [6]. The geometric means of the total nitrogen and phosphorus contents in the sampled effluent samples should not exceed $20 \text{ mg}\cdot\text{L}^{-1}$ (or at least show a reduction of 70 wt.%) and $1.0 \text{ mg}\cdot\text{L}^{-1}$ (or at least show a reduction of 80 wt.%), respectively [7]. Passenger ships without on-board sewage treatment plant installations must discharge generated sewage to port reception facilities (PRFs) [6].

Food waste is generated in all types of galleys and dining areas. The term “food waste” in MARPOL Annex V includes all damaged and undamaged foodstuffs, consisting of fruits, vegetables, dairy products, meat products, and many other food scraps, that can be found on board ships [5].

The regulation considers food waste to be biodegradable and non-hazardous. Therefore, such waste can be discharged into the Baltic Sea as far as practicable if a ship is on a route that is not less than 12 nautical miles from the nearest shore. The regulation demands the comminution or grinding of food waste into a substance that can be extruded through a grid-type screen with an opening size up to 25 mm for ships located at least 12 NM from the nearest shore [5].

1.1. Problems of Pollution in the Baltic Sea Area

The European Environment Agency has recently produced an alarming report about contamination levels in the European seas. The Baltic Sea is 96.3% polluted and recognized as the most polluted sea in the European region, which has been driven by an increase in negative pressures and stress on the sensitive Baltic Sea ecosystem [8].

Scientists have identified eutrophication as a severe and profoundly ecological problem in the Baltic Sea area [9]. It is a process that occurs when anthropogenic pollution of water leads to an increased amount of nutrients or nitrogen and phosphorus, which changes the balance of the ecosystem and deteriorates the water quality [10]. The amount of nutrients in the Baltic Sea has increased several times over the last century, and the slow exchange of water

contributes to the retention of these nutrients in the sea for up to 25 years [11]. Therefore, the recovery of the Baltic Sea ecosystem depends on nutrition reduction.

1.2. “Footprint” of the Shipping Vector in the Baltic Sea

The best practical approach for food waste management can vary in different ships due to the limitations in directly applying the regulation [12].

Food waste biodegradability is typically determined by the amounts of carbohydrates, proteins, lipids, and residues of inorganic compounds. However, the decomposition process and intensity also vary depending on the type of food and its ingredients. For example, if food waste consists of rice and vegetables, it will be high in carbohydrates, while that consisting of meat and eggs will be high in protein and lipids [13]. However, food waste discharged into the sea is not homogeneous. It can be in raw or ground form, with colloidal and suspended particles of sizes up to 25 mm. In addition, waste particles also tend to stick together, forming a dense, sticky slurry. Studies have shown that ground food waste discharged into the sea can disperse the surface water layer [14]. For example, the peels of onions and other vegetables can withstand the grinding process and pass through the 25 mm opening almost unchanged. Solid waste, such as bones and one-piece unground waste, sinks to the seabed, where degradation processes begin. However, in shallow areas such as the Baltic Sea, it can accumulate on the seabed. In turn, the emulsified and colloidal particles remain suspended in the water column and, if insufficient mixing takes place, they locally increase the turbidity of the water [14]. Consequently, food waste discharged into the Baltic Sea can contribute to eutrophication processes during structural degradation in water.

Nitrogen and phosphorus contents determine the nutritional value of food products [13]. Unconsumed solid food waste contains several times higher concentrations of nitrogen than phosphorus [15]. The nitrogen content of solid food waste can typically vary from 8.5 up to 43 g·kg⁻¹, while the phosphorus content ranges from 4.2 up to 8 g·kg⁻¹ [16].

The entirety of the wastewater consisting of homogenized food waste and greywater suspension can be essentially classified as food waste within the scope of the MARPOL 73/78 requirements and, therefore, discharged according to the same principles [5].

However, ships must store food waste in an on-board storage tank when located in a port area or, when closer than 12 nautical miles to the nearest land, in a “special area”. Soft organic food waste separated from solid waste can be stored in labelled and sealed containers. Containers may be placed in specifically designed rooms or even in rooms equipped with refrigerators.

Researchers have predicted potential risks from high nutrient pollution that could jeopardize the recovery of the Baltic Sea from eutrophication. However, there is not enough data for more accurate assessment of pollution by ships operating under the current regulations in force. Therefore, this study aimed to assess the potential threats to the Baltic Sea under different waste management scenarios that could contribute to eutrophication, with the intention of reducing the probability of such pollution risks. The results of the presented case study reveal that ship operators manage ship-generated sewage and food waste under different scenarios without violating regulatory requirements. On the other hand, physicochemical tests show relatively high concentrations of nutrients in tested “greywater” samples. As a result, researchers have expressed concern about the possibility of ship operators legally spilling mixtures of untreated “greywater” with chopped food scraps into the Baltic Sea 12 NM from nearby land, in areas represented as the busiest sea transport routes.

Furthermore, the results are of interest for other researchers and for governing organizations due to heightened ecological problems and the area’s special status in the MARPOL 73/78 Convention on Waste Management.

2. Methods

We adopted a model that integrates the basic principles developed by Covello and Merkhofer (1993) [17] to assess the Baltic Sea's potential risk of nutrient pollution, as demonstrated in Figure 2 and discussed in detail below.

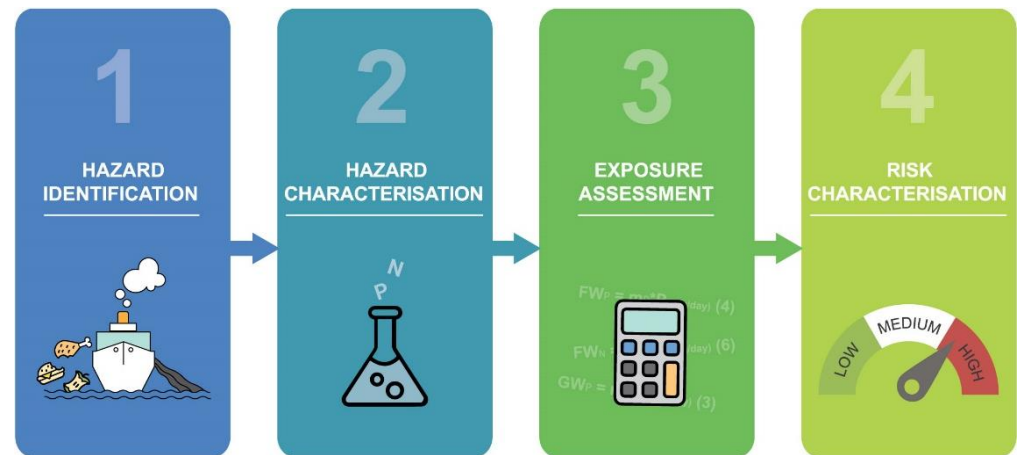


Figure 2. A visual representation of a four-stage operational model for assessment of pollution risk arising from sea environment eutrophication. We adopted the presented approach [17] to identify and characterize food waste-related hazards, assess exposure, and describe pollution risks.

2.1. First Stage—Hazard Identification

In this stage, we analysed food waste management tendencies on ships sailing in the Baltic Sea from 3 June 2020 to 7 July 2020.

Shipping companies have a notable incentive to publicize their efforts in implementing the IMO guidelines on ship-source pollution, focusing on the detection of waste management trends. These measures relate to the growing public concern about the recovery of the Baltic Sea. We selected publicly available information provided by company operators on their websites for the initial study and data analysis. Data were collected from the HELCOM (2015) list of reported shipping companies operating in the Baltic Sea area and studied selectively [18].

We selected and applied the synonyms “sewage”, “waste”, “black water”, “greywater” or “dirty water”, “food waste”, “solid food waste”, and “sorted waste” as inputs to internet search engines (Google, Yandex, etc.) in different combinations. Reports published on the websites of 27 ferry lines and 36 cruise companies were researched and analysed. In addition, an online questionnaire was created and published to obtain responses from respondents who were working on board in galleys and could deal with existing practices in food waste management on board ships.

2.2. Second Stage—Hazard Characterisation

We collected liquid greywater (waste) samples with the possible presence of homogenized food waste from three different cargo ships (about 10 L from each ship) in the ports of Klaipeda, Riga, and Helsinki between August and September 2020. The collected greywater samples were transported to an accredited laboratory for further chemical and physical analyses. Standardized test methods were selected and applied according to ten different indicators, as shown in Table 1. Total nitrogen and phosphorus concentrations and biochemical and chemical oxygen demand indicators were applied as the most critical indicators for determining eutrophication risk factors.

Table 1. The list of applied greywater testing methods for the determination of selected indicators and subsequent assessment of eutrophication risk factors.

No.	Indicator	Applied Testing Standard	Testing Method
1	Ammonium nitrogen (NH ₄ /N)	LVS ISO 7150-1:1984	Spectrophotometry
2	Nitrate nitrogen (NO ₃ /N)	LVS ISO 13395:2004	Spectrophotometry
3	Nitrite nitrogen (NO ₂ /N)	LVS ISO 6777:1984 + AC:2001	Spectrophotometry
4	Total nitrogen (N _{Total})	LVS EN ISO 29441:2011	Combination of flow analysis and spectrometric detection
5	Phosphate phosphorus (PO ₄ /P)	LVS EN ISO 6878:2005:4 p.	Spectrophotometry
6	Total phosphorus (P _{Total})	LVS EN ISO 6878:2005:7 p	Spectrophotometry
7	Chemical oxygen demand (COD)	LVS EN ISO 15705:2002	Photometric
8	Biochemical oxygen demand (BOD ₅)	LVS EN 1899-1:2003	Dilution and seeding method
9	Suspended substances (SSs)	LVS EN 872:2005	Gravimetry
10	pH	LVS EN ISO 10523:2012	Electrometric

Additionally, solid substances were separated from greywater samples and characterized with physical and chemical methods.

2.3. Third Stage—Exposure Assessment

We used the results of the information evaluation and the data obtained in the previous steps to assess the potential hazards with respect to the requirements of MARPOL 73/78, quantifying and comparing the amount of waste pollution contributing to eutrophication.

2.4. Fourth Stage—Risk Characterisation

We describe the potential risk of contamination in existing food waste management scenarios in the framework of this study. The qualitative assessment followed the recommendations of Det Norske Veritas (DNV) [19]. The investigation resulted in recommendations for improved waste management and required behavioural changes to reduce the potential risk resulting from food waste and related contaminants.

3. Results and Discussion

3.1. Identified Hazards

3.1.1. Trends in the Management of Waste from Passenger and Cruise Ships

The frequencies of the different synonyms applied to food waste and greywater found in cruise and ferry ship operators' webpages by using search engines (Google, Yandex, etc.) are shown in Figure 3. Companies apply these synonyms in informative sections for any interested website visitors in order to exhibit the approach used for treating their ships' generated sewage.

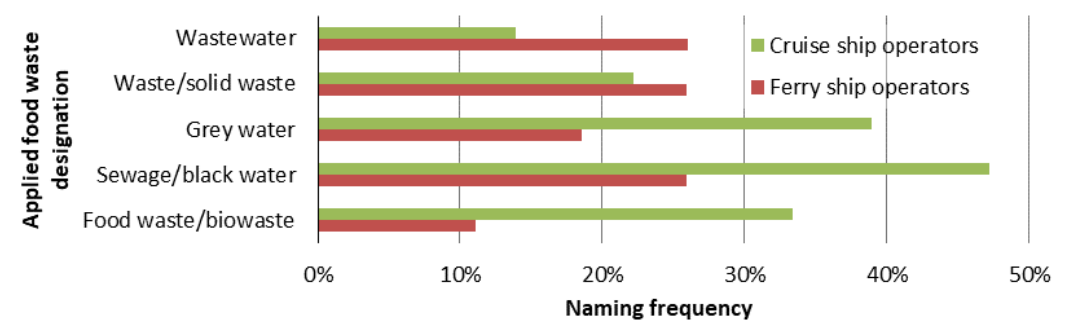


Figure 3. The frequencies of different synonyms applied to food waste and greywater found using search engines (Google, Yandex, etc.) in descriptive sections of cruise and ferry ship operators' webpages dealing with the management of such waste.

The results of information analysis for the data found on the websites of 27 ferry line companies revealed that most ferry operators (more than 70%) did not specify waste management in terms of efforts to reduce eutrophication through, e.g., food waste, sewage, or greywater. We discovered “food waste” or its synonyms in 11% of visited websites. Shipping companies applied the terms “solid waste” or “waste” in 26% of all cases. This type of waste could theoretically contain food waste. Shipping companies mentioned “greywater” in 19% of the websites reviewed. Shipping companies used “wastewater” slightly more frequently (26%) than the synonyms “food waste” (11%) and “greywater” (19%), as demonstrated in Figure 3.

Ferry operators provide more detailed analyses on their websites in the case of “food waste” discharge to PRFs. Operators using the terms “waste” or “solid waste” emphasized the delivery of these wastes to the landfill.

A study of 36 cruise ship companies’ websites revealed that the term “food waste” was mentioned more often than by ferry operators. “Food waste” was found on 33% of cruise ship websites, while in 22% of cases “waste”/“solid waste” was mentioned, which may also have included food waste. Furthermore, about 47% of cruise companies used “sewage” on their websites, while 39% of cruise ship operators selected the synonym “greywater”. Only five cruise companies applied the term “wastewater”.

The further analysis found that 12 cruise ship operators used “food waste”. Of these, more than half had indicated disposal of food waste at sea, either as the only applied food waste management scenario or in combination with discharge to the PRFs at port or incineration. Four operators also mentioned combined incineration and discharge to PRFs. One of the assessed cruise ship operators described food waste dehydration into a compact form and delivery to the port for further processing.

Cruise ship operators using the terms “waste”, or “solid waste” were analysed separately. Six of the eight operators reported waste discharge to PRFs and two of them performed waste incineration. In addition, one of the cruise ship operators compressed the waste before releasing it to PRFs. Finally, one of the reviewed cruise ship operators mentioned waste treatment but did not provide a detailed characterization of the process.

3.1.2. Trends in Ships’ Waste Management

The food waste management survey involved 42 respondents whose work on board was basically or partially related to food waste handling for the galley. We recorded respondents’ answers in accordance with the confidentiality agreement. Of the respondents, 8 worked as cooks and 22 as cook assistants. Furthermore, 12 cook assistants identified themselves as cadets in the period from 2019 to 2020.

The respondents of the survey worked or had worked on different types of ships during the survey period. In total, 20 respondents were active sailors on tankers and 7 worked on tankers before the period of the survey. In addition, three respondents worked on general cargo ships and five respondents worked as cadets on general cargo ships. Seven respondents worked on passenger and cruise ships, i.e., five respondents worked on passenger ships and two on cruise ships.

We divided the questionnaires into three groups before statistical data processing and analysis. The first group consisted of the answers from 23 respondents who worked on transport ships and the second group consisted of the responses from 12 respondents (cadet cook assistants) from transport ships as well. The third group consisted of seven respondents who worked on passenger and cruise ships.

Responses to the question “When is the food waste treatment on board?” were as follows:

- During sailing on the open waters in the Baltic Sea;
- Close to the shore;
- While anchored in a port.

The obtained responses revealed the different food waste management strategies on board ships, as demonstrated in Figure 4a–g. In addition, the management strategies were affected by the specific situations in which the vessels may have been during voyages.

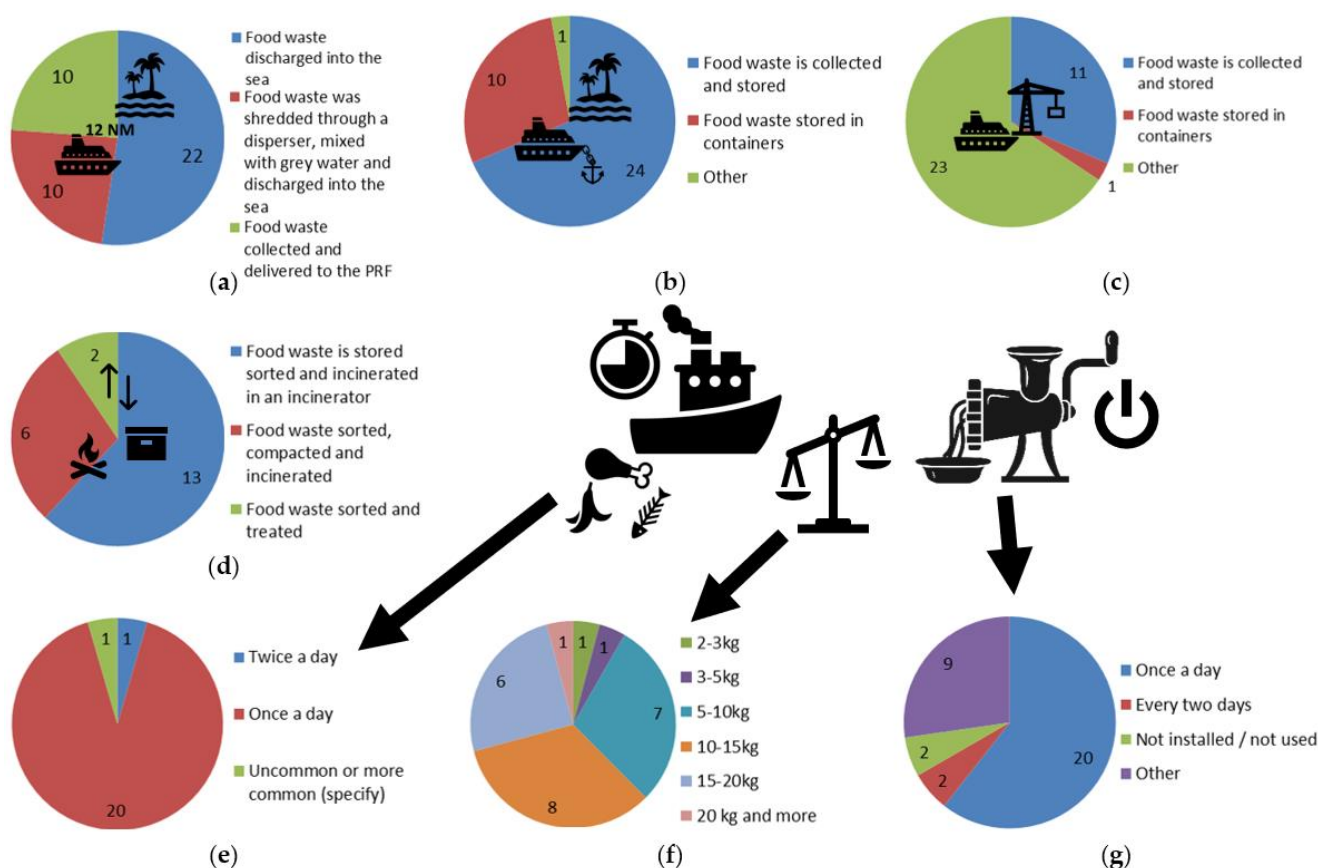


Figure 4. The numerical distributions of answers from respondents about the specific location for food waste treatment: (a) in open waters of the Baltic Sea area (further than 12 NM from the shore); (b) closer than 12 NM to the nearest land; (c) while anchored in a port; and (d) added explanation: “other”. The respondents also provided statistical information about (e) the frequency and (f) the amount of shredded or ground food waste disposed at sea and about (g) the operating frequency of the food waste shredder. The attached icons indicate described situations and processes.

The 17 respondents of the first group and 5 respondents from the second group indicated the answer “food waste discharged into the sea” for the case in which ships were sailing in the open waters of the Baltic Sea area (further than 12 NM from the shore), as demonstrated in Figure 4a. Furthermore, six respondents from the first group and four respondents from the second group indicated the response “food waste was shredded through a disperser, mixed with greywater and discharged into the sea”. Three respondents from the second and seven respondents from the third groups marked the answer “food waste collected and delivered to the PRFs”. As the respondents from the third group noted that “food waste was collected and discharged to the PRFs”, they were excluded from the rest of the survey.

Seventeen responses from the first group and seven responses from the second group indicated “food waste collected and stored” with regard to a described situation of a vessel being located close to the shore, as demonstrated in Figure 4b. Finally, six respondents from the first group and four respondents from the second group indicated that “food waste was stored in containers” but one respondent selected “other” without any additional explanation.

Seven respondents from the first group and four respondents from the second group indicated “food waste collected and stored”. One of these respondents also indicated that “food waste is stored in a container” when the vessel is anchored in the port, as demonstrated in Figure 4c.

Sixteen respondents from the first group and seven respondents from the second group chose “other”. In total, 14 respondents from the first group and 7 respondents from the second group added an explanation:

- Thirteen responses—“food waste was stored, sorted, and incinerated”;
- Six responses—“food waste was sorted, compacted, and incinerated”.

Two respondents indicated that “food waste was sorted and treated” but did not provide a detailed explanation, as shown in Figure 4d.

We concluded that all the interviewed respondents who had worked in the transport fleet during or before the survey applied discharge into the Baltic Sea in terms of the food waste management practice described in MARPOL 73/78. In addition, seven respondents working on passenger and cruise ships indicated that food waste was collected and discharged to PRFs.

Food waste can also be collected and incinerated outside territorial waters in order to meet the MARPOL 73/78 requirements for the Baltic Sea area. Ships visiting a port in the Baltic Sea region pay a sanitary fee at a specific rate. The cost depends on the type of ship and the gross tonnage and includes payment for specified waste reception services [20]. For example, the Freeport of Riga determines the sanitation fee for 15 m³ of waste as defined in MARPOL Annex V [21]. The shipping company must pay the presented cost independently of the fact of discharge. The payment for waste increases in accordance with the tariff defined by the service provider for cases that exceed the default limit. In addition, transport vessels have a higher sanitary fee compared to passenger and cruise ships.

The results of further analysis of the questionnaire indicated that respondents worked on transport vessels with crews of over 20 crewmembers. Seventeen responses from the first group and five responses from the second group stated that “food waste was discharged to sea”; therefore, the question, “How often is shredded or ground food waste discharged into the sea?” was additionally asked, as demonstrated in Figure 4e.

Sixteen respondents from the first group and four respondents from the second group indicated that the discharge of mostly shredded or ground food waste into the sea occurred once a day. One respondent reported that such an activity occurred twice a day. The first group of respondents acknowledged that the frequency of food waste discharge differed due to visits to ports in which operators discharged all waste (including food waste) to PRFs.

The following question, “Approximate amount of food waste discharged into the sea each time,” allowed us to clarify the approximate amount of food waste discharged into the Baltic Sea. The answers offered varied within the range of a few kilograms, as shown in Figure 4f.

The obtained data indicated that 10–15 kg of food waste is generally disposed of at sea each time.

Both the group of respondents who had previously indicated that “food waste was discharged at sea” and those who indicated that “food waste was stored in a tank, mixed with greywater and discharged into the sea” answered the question, “How often was the food waste shredder used (if installed)?” with the answer that the “food waste shredder is operated once a day”, as shown in Figure 4g. Two respondents indicated that the food chopper was operated every two days. However, nine respondents chose a different answer, explaining that the shredder was used when necessary.

Generally, the responses obtained revealed that the food shredder was frequently used on board transport vessels for daily purposes.

The ten respondents who had previously stated that “food waste was stored in a tank, mixed with greywater and discharged into the sea” received the following question: “How much food waste is ground during the day?” The answers from these respondents varied within a range of a few kilograms. We would like to emphasize that none of the respondents marked the weight range of ground food waste from 1 up to 3 kg per day. The principal amount of ground food waste reported by the seven respondents ranged from 3 to 5 kg. Three respondents from both groups indicated that the amount of food waste ranged

from 5 up to 10 kg. Also, none of the respondents chose the option “other” as the answer. Thus, the data show that the predominant amount of ground food waste stored in the tank and mixed with greywater before discharge into the sea was significantly lower than the amount of food waste discharged into the sea itself. Finally, we asked the concluding question: “Are there other methods used in the management of food waste on board that are not mentioned in this survey?” Five respondents from the first group indicated that “due to disposal restrictions or due to sanitary difficulties, food waste is placed in a room where it is cooled or frozen”. However, the other 30 respondents indicated that operators did not apply other food waste treatment or disposal methods on board vessels.

3.2. Physical/Chemical Characterization of Identified Hazards in Greywater

The set of three greywater samples collected from transport vessels were physically/chemically tested in a specialized water-testing laboratory using standardized and accredited methods that meet the requirements of the MEPC.227 (64), as demonstrated in Table 1 [7]. We determined ten different physical/chemical parameters, and the resulting concentrations of pollutants measured in the collected samples differed significantly, as shown in Table 2.

Table 2. Measurement test results and maximum values permitted by the normative requirements of the MEPC.227 (64) (Annex 22) for the outputs after sewage treatment of discharge according to the requirements of MARPOL Annex IV.

No.	Determined Indicator	Tested Samples			MEPC.227 (64) (Annex 22) [7]
		S ₁	S ₂	S ₃	
1	Ammonium/nitrogen (NH ₄ /N), mg·L ⁻¹	163 ± 16	69 ± 7	0.9 ± 0.03	-
2	Nitrate nitrogen (NO ₃ /N), mg·L ⁻¹	0.59 ± 0.05	0.26 ± 0.03	0.1 ± 0.03	-
3	Nitrite nitrogen (NO ₂ /N), mg·L ⁻¹	0.07 ± 0.07	0.12 ± 0.01	0.03 ± 0.003	-
4	Total nitrogen (N _{Total}), mg·L ⁻¹	238 ± 24	75 ± 7	1.3 ± 0.1	20
5	Phosphate phosphorus (PO ₄ /P), mg·L ⁻¹	66.8 ± 6.7	21.6 ± 2.2	1.04 ± 0.05	-
6	Total phosphorus (P _{Total}), mg·L ⁻¹	71 ± 7	22 ± 2	1.67 ± 0.08	1
7	Chemical oxygen demand (COD), mgO ₂ ·L ⁻¹	1272 ± 127	570 ± 57	257 ± 26	125
8	Biochemical oxygen demand (BOD ₅), mgO ₂ ·L ⁻¹	763 ± 76	399 ± 40	150 ± 15	25
9	Suspended substances (SSs), mg·L ⁻¹	881 ± 88	335 ± 34	77 ± 7.6	35
10	pH	6.8 ± 0.1	7.4 ± 0.1	7.8 ± 0.1	6.0–8.5

The sewage discharge of samples S₁ and S₂ exhibited exceedingly high nutrient concentrations compared to the maximum values allowed by the MEPC.227 (64). These results indicate the insufficient effect of applied treatment procedures.

These results exceeded even the typical values in municipal wastewater, i.e., nitrogen (organic compounds and ammonium salts) ranges from 40 up to 74 mg·L⁻¹ and phosphorus from 8 up to 13 mg·L⁻¹ [22,23]. The high concentration of ammonium ions in samples S₁ and S₂ indicated food waste with a high protein concentration. The nitrogen concentration exceeded the phosphorus content in the tested shredded solid food waste [13,15,16]. In addition, samples S₁ and S₂ exhibited pH values of 6.8 and 7.4, respectively (below pH = 8), which is what ensured that the nitrogen-ammonium form did not change into the reduced form of ammonia (NH₃), which creates odour and the potential for corrosion [23]. The physical/chemical test of sample S₃ demonstrated the kind of sufficiently low nutrient content and reduced pollution risks that would be ideal when ship operators discharge such greywater in the marine environment.

Samples S₁ and S₂ had high ammonium ion concentrations (N-NH₄) and large amounts of phosphate ions (P-PO₄). Therefore, phytoplankton would consume them as natural nutrients if such contaminants were released into the marine environment [24].

The high organic matter content in samples S_1 and S_2 was related to the presence of food waste. This parameter can also be indicated by the chemical oxygen demand (COD) and biochemical oxygen demand (BOD_5), as these can increase by 17 up to 62% [25].

Samples S_1 and S_2 contained significant amounts of suspended substances (SSs) and these exceeded the amount specified in the MEPC.227 (64) for treated sewage [7]. Sample S_1 had several times higher amounts of SSs than typical municipal wastewater, where the amount of SSs is between 199 and 430 $mg \cdot L^{-1}$. The compositions of SSs may differ, which can indicate the presence of shredded food waste, as concentrations of SSs can increase by 1.9 up to 7.1% [25]. Observed SSs may not always be biodegradable in relatively short timespans as they may contain substances of different origins. Therefore, in-depth research is required [23].

3.3. The Calculation and Exposure Assessment Results for Discharged Food Waste

The survey results obtained in the first stage of the study (Section 2.1) made it possible to determine the prevailing food waste management scenarios on transport vessels and calculate the amount of food waste generated in a day. Then, we applied the arithmetic means of the waste amounts in calculations in accordance with the range for the amounts of food waste indicated in each respondent's answer (for cases of discharge of food waste alone or mixed with greywater, according to MARPOL 73/78 requirements).

It was found that 244.5 kg of reported (by 23 respondents) food waste was produced on board for "discharge" from various tanker-type vessels. Of this amount, the operators directly discharged 210 kg of food waste from 16 ships directly into the sea waters and 34.5 kg from 7 ships after homogenization into greywater and subsequent separation. In addition, the crews of three container-type vessels produced and discharged 32.5 kg of food waste.

Crews of general cargo/dry cargo-type vessels generated 50.5 kg (in total) of food waste from seven ships. Operators from two of these ships discharged 30.0 kg into sea waters, but 20.5 kg from five ships was processed through homogenizers and mixed with greywater before being released into the sea.

The results of the survey also revealed the number of crewmembers (persons) on respondent vessels. This factor made it possible to calculate the amount of food waste generated for "discharge" in each specific type of vessel per person per day, taking into account food waste management scenarios, as well as the average amount of food waste generated on that type of ship, according to the Equation (1):

$$FW_{person/day} = \sum_{i=1}^n \frac{M}{P}, \quad (kg \cdot number\ of\ persons \cdot days^{-1}) \quad (1)$$

where:

- $FW_{person/day}$ —the average amount of food waste generated by each person per day (kg);
- M —the total amount of food waste generated on the ship ($kg \cdot day^{-1}$);
- P —number of persons (crewmembers).

We estimated that the amount of food waste produced on board tankers with subsequent discharge into the sea ranged from 0.395 up to 0.833 $kg \cdot person \cdot day^{-1}$ and when the food waste went through a disperser and was mixed with greywater and then discharged into the sea, it ranged from 0.235 to 0.395 $kg \cdot person \cdot day^{-1}$. The amount of food waste produced and removed into the sea from container vessels ranged from 0.375 to 0.775 $kg \cdot person \cdot day^{-1}$.

Operators directly discharged amounts of food waste in a range between 0.625 and 0.833 $kg \cdot person \cdot day^{-1}$ into the sea from cargo ships and only 0.107–0.469 $kg \cdot person \cdot day^{-1}$ was shredded and dispersed in greywater before discharge.

We summarize the average food waste generation for each type of vessel in Table 3. Again, the concern arises of the average amount of "wasted" food that is expected to be produced and which is likely to be discharged into the Baltic Sea.

Table 3. The estimated average amounts of food waste generated and discharged, alone or together with greywater, by different ships.

Type of Vessel	Food Waste Discharge or Generation Ratios (kg·Person·Day ⁻¹)		
	Food Waste Discharged into Environmental Sea Waters	Food Waste Mixed with Greywater and Discharged to Environmental Sea Waters	Estimated Average Amount of Generated Food Waste
Tankers	0.571	0.329	0.900
Container cargo	0.508	-	0.508
General/dry cargo	0.729	0.328	1.057
Container cargo and general/dry cargo (average)	0.619	0.328	0.783

Remarkably, there are transport vessels designed in such a way that ship operators can crush the soft parts of the food waste in a disperser installed in the sink by adding fresh water, rinsing the waste through a pipeline into a greywater tank, and discharging the mixture into the sea [12]. In these cases, the contents of the entire tank are classified as food waste, and the discharge is not violated [26]. On-board operators apply this approach as general practice. In addition, the percentage of food waste shredded in a disperser, mixed with greywater, and discharged into the sea in comparison to the waste that is transferred to PRFs or incinerated is different for each ship, and the Garbage Record Book is relatively approximate. Consequently, the amount of food waste varies over an extensive range [12]. Data published in various literature sources concerning on-board food waste per person per day also show relatively large variations, as demonstrated in Table 4.

Table 4. Estimation of average amount of food waste generated by one person every day on different vessels according to literature data.

Type of the Vessel	Estimated Food Waste Generation Rate (kg·Person·Day ⁻¹)	References
Tankers	0.48	[16,19]
Cargo	0.67	[16,19]
	0.36	[16]
Navy	0.6 (crew of about 30 persons)	[15]
	0.95 (crew of about 200 persons)	
	1.00 (crew of about 250 persons)	
Cruise	Up to 3.5	[27]
	From 1.3 up to 3.5	[28]
Passenger ships	1.04	[16,19]
Fishing ships	0.28	[16,19]
Offshore ships	0.21	[16,19]
Not specified	From 1.4 up to 2.4	[29]
	0.75	[15]

Ships discharge greywater with 159 tons of nitrogen and 26 tons of phosphorus in the Baltic Sea every year, in addition to the nutrients generated by food waste.

Governing organizations have not applied specific rules or limitations for managing or treating such waste before discharge into seawater, nor is there a specific requirement to transfer waste to PRFs [30]. As a result, the transfer to ports is voluntary. The amount of greywater produced varied in a range from 105 to 119 L·person·day⁻¹ among the types of vessels discussed in this study, as demonstrated in Table 5. In addition, the total emissions of nutrients (nitrogen and phosphorus) from greywater were about 3.8 and 2.6 times higher compared to those from food waste, respectively.

Table 5. Estimated volumes of generated greywater discharged from different ship types and assessed average factors for nutrients used in modelling in previous studies.

Type of Vessel	Estimated Volume of Greywater Generation Rate (L·Person·Day ⁻¹) [30]	
Tankers	105	
Container cargo and general/dry cargo (average)	119	
	Average emission factors for nutrients used in the modelling process (g·person·day ⁻¹) [30,31]	
Type of Effluent	Phosphorous (P)	Nitrogen (N)
Greywater	1.9	4.4
Food waste	0.5	1.7

Results of Daily Nutrient Content Model Calculations

The number of crew members was essentially an influencing factor in the daily nutrient content results. According to the survey data, most of the crews consisted of over 20 persons. These were considered large transport vessels. Therefore, there may have been a practical difference from the small-sized vessels (with small numbers of crewmembers) in terms of their discharge management and volumes [12]. Thus, the total sum of these daily nutrient content (DNC) calculation options was used to determine the total amount of these substances. This parameter depended on the amounts of catering waste produced by the different numbers of persons on each type of ship and the amounts of greywater produced by the different numbers of persons on all types of ship [31]. In the worst-case food waste management scenario, a ship discharges a mixture of food waste and greywater when the DNC has been generated. We calculated this according to the following equations (Equations (2)–(6)):

$$\text{DNC}_B = \text{GW}_P + \text{FW}_P + \text{GW}_N + \text{FW}_N, (\text{g} \cdot \text{day}^{-1}) \quad (2)$$

where:

- GW_P —the quantity of phosphorus in the greywater in one day ($\text{g} \cdot \text{day}^{-1}$);
- FW_P —the quantity of phosphorus in the food waste in one day ($\text{g} \cdot \text{day}^{-1}$);
- GW_N —the quantity of nitrogen in the greywater in one day ($\text{g} \cdot \text{day}^{-1}$);
- FW_N —the quantity of nitrogen in the food waste in one day ($\text{g} \cdot \text{day}^{-1}$).

The quantity of phosphorus in the greywater was determined as follows:

$$\text{GW}_P = m_P \cdot P_P, (\text{g} \cdot \text{day}^{-1}) \quad (3)$$

where:

- m_P —daily production of phosphorus in greywater per person: 1.9 g;
- P_P —average number of persons on board a typical cargo ship: 20.

The quantity of phosphorus in the food waste was determined as follows:

$$\text{FW}_P = m_P \cdot P_P, (\text{g} \cdot \text{day}^{-1}) \quad (4)$$

where:

- m_P —daily production of phosphorus in food waste per person: 0.5 g;
- P_P —average number of persons on board a typical cargo ship: 20.

The quantity of nitrogen in the greywater was determined as follows:

$$\text{GW}_N = m_N \cdot P_P, (\text{g} \cdot \text{day}^{-1}) \quad (5)$$

where:

- m_N —daily production of nitrogen in greywater per person: 4.4 g;
- P_p —average number of persons on board a typical cargo ship: 20.

Finally, the quantity of nitrogen in the food waste was determined as follows:

$$FW_N = m_N \cdot P_p, (\text{g} \cdot \text{day}^{-1}) \quad (6)$$

- m_N —daily production of nitrogen in food waste per person 1.7 g;
- P_p —average number of persons on board a typical cargo ship: 20.

The area of the Baltic Sea marked with a blue line in Figure 5 shows the territorial boundaries of the waters (at least 12 NM from the nearest land) [32], where ship operators may discharge food waste and greywater into the sea in accordance with the MARPOL Convention (after homogenization and screening through a sieve with an opening size up to 25 mm). Ships closer than 12 NM are required to collect the food waste for release into PRFs. The list of the ports most visited by cruise ships in 2014 [18] indicates the availability of the largest PRFs.

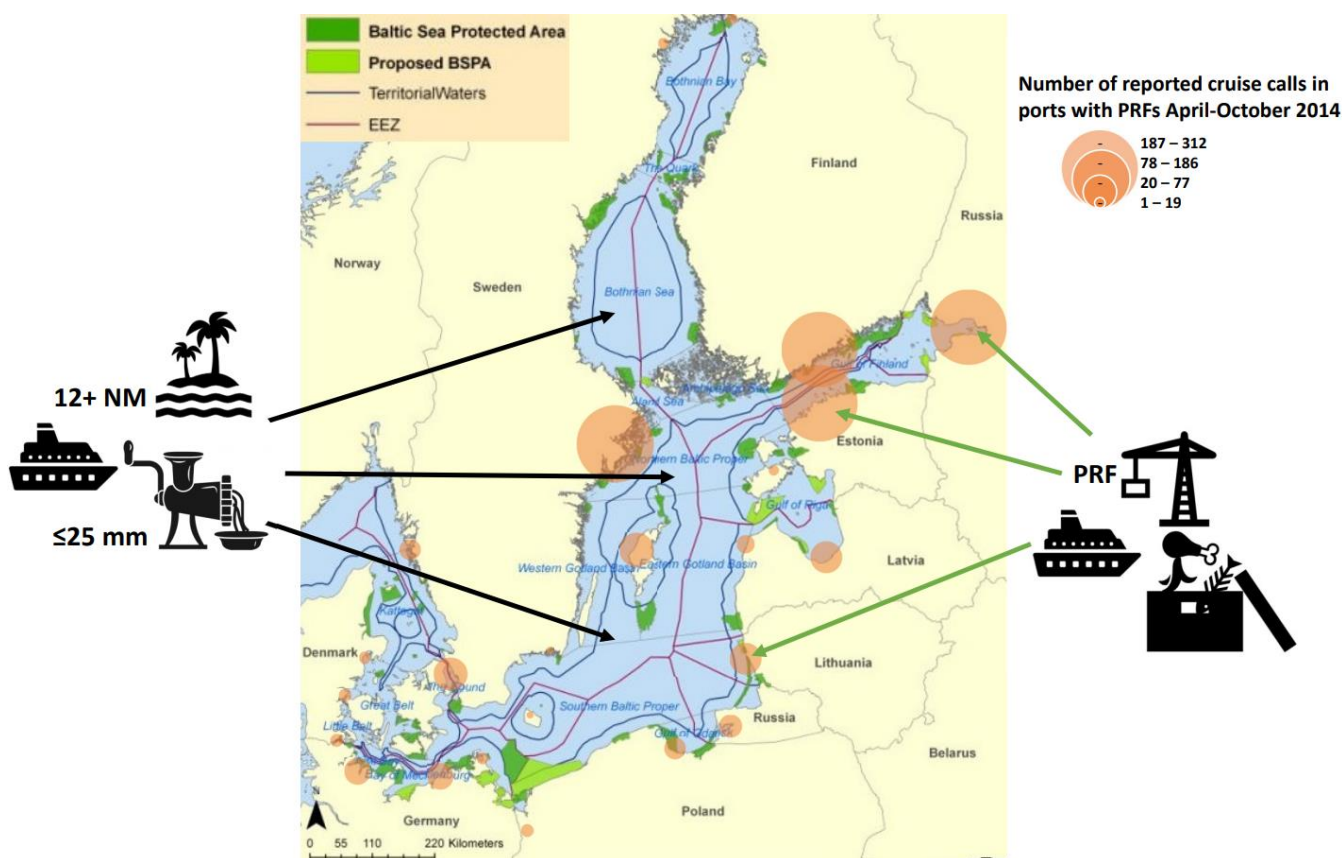


Figure 5. The Baltic Sea and locations of its sub-basins. The blue line shows the border of territorial waters (at least 12 NM from the nearest land) and the purple lines indicate the Exclusive Economic Zones (up to 3 NM from the nearest land). The green colour indicates existing (dark green) and proposed (light green) protected areas. Image from HELCOM, Baltic Sea protected areas map, 2008 [32], in combination with the list of ports most visited by cruise ships in 2014 [19], indicating the availability of the largest PRFs.

In the food waste management scenario in which food waste and shredded food waste mixed with greywater are discharged into the sea, the daily nutrient content DNC_{B1} contributes a discharge of $48 \text{ g} \cdot \text{day}^{-1}$ of phosphorus and $122 \text{ g} \cdot \text{day}^{-1}$ of nitrogen to the Baltic Sea.

In the food waste management scenario in which only food waste is discharged into the sea, DNC_B contributes $10 \text{ g}\cdot\text{day}^{-1}$ of phosphorus and $34 \text{ g}\cdot\text{day}^{-1}$ of nitrogen to the sea. Nutrient emission factors from literature sources [30,31] were used in these calculations.

We performed DNC_B calculations based on the results of physical/chemical analysis of the water samples S_1 , S_2 , and S_3 (Table 2) and approximate volumes of greywater in tankers (L/person and day) from literature source [30,31], i.e., 105 L per person was assumed to be used on a tanker per day. In addition, the use of food grinders consumes an additional 4.3 L of water per person per day [25]. Therefore, in the food waste management scenario in which shredded food waste is mixed with greywater, the calculation followed Equations (7) and (8).

The phosphorous-containing daily nutrient content (DNC_B) wasted to the Baltic Sea was determined as follows:

$$DNC_B = GW_B \cdot P_P \cdot m_P \text{ (g)} \quad (7)$$

where:

- GW_B —estimated volume of greywater on board tankers ($\text{L}\cdot\text{person}^{-1}\cdot\text{day}^{-1}$): 109.3 L;
- P_P —average number of persons on board tankers: 20 crewmembers;
- m_P —total phosphorus content of sample S_1 : $71.00 \text{ mg}\cdot\text{L}^{-1}$;
- m_P —total phosphorus content of sample S_2 : $22.00 \text{ mg}\cdot\text{L}^{-1}$;
- m_P —total phosphorus content of sample S_3 : $1.67 \text{ mg}\cdot\text{L}^{-1}$.

Finally, the nitrogen-containing daily nutrient content (DNC_B) wasted to the Baltic Sea was determined as follows:

$$DNC_B = GW_B \cdot P_P \cdot m_N \text{ (g)} \quad (8)$$

where:

- GW_B —estimated volume of greywater on board tankers ($\text{L}\cdot\text{person}^{-1}\cdot\text{day}^{-1}$): 109.3 L;
- P_P —average number of persons on board tankers: 20 persons (crewmembers);
- m_N —total nitrogen content of sample S_1 : $238.00 \text{ mg}\cdot\text{L}^{-1}$;
- m_N —total nitrogen content of sample S_2 : $74.50 \text{ mg}\cdot\text{L}^{-1}$;
- m_N —total nitrogen content of sample S_3 : $1.26 \text{ mg}\cdot\text{L}^{-1}$.

According to these calculations, the DNC_{B2} from sample S_1 would give the Baltic Sea 155.21 g of phosphorus and 520.27 g of nitrogen. The DNC_{B3} of S_2 would provide 48.09 g of phosphorus and 162.86 g of nitrogen, while the DNC_{B4} of S_3 would add only 3.65 g of phosphorus and 2.75 g of nitrogen to the sea if the greywater were discharged into the Baltic Sea.

If the calculations are based on the data specified by the requirements of the MEPC.227 (64) for treated ship effluents allowed to be discharged into the Baltic Sea and we determine the volumes of effluent per person per day according to literature data, i.e., 105 L greywater but 36.7 L black water [30,31], then for a tanker with 20 crewmembers the permissible input to the Baltic Sea is DNC_{B5} 56.68 g of nitrogen and 2.83 g of phosphorus.

The distribution of mixed food waste and greywater discharge into the Baltic Sea (Figure 5) is concentrated in areas from which it is further than 12 NM from the nearest land to the main shipping lines (Figure 1).

3.4. The Result of Risk Characterization

A risk matrix, based on the practice recommended by Det Norske Veritas (DNV), was used in the qualitative assessment of the impact of the DNC load from food waste management on the Baltic Sea environment, as shown in Table 6.

The use of the matrix involves the assessment of the probability of the occurrence of effects of different types of food waste management on the Baltic Sea using four categories (from very unlikely to very likely) and of the environmental consequences in categories ranging from insignificant to highly serious, which are characterized by the impact of the DNC load.

Table 6. DNC risk assessment matrix for food waste management in the Baltic Sea environment (adopted from [19]).

Description	Environment	Probability Increases			
		Very Unlikely (A)	Unlikely (B)	Probably (C)	Highly Likely (D)
Highly serious (1)	DNC load effect is not acceptable	A1	B1	C1	D1
Serious (2)	DNC load effect is tolerable	A2	B2	C2	D2
Moderate (3)	DNC load effect is acceptable	A3	B3	C3	D3
Insignificant (4)	DNC load effect is negligible	A4	B4	C4	D4
Description of risks					
High	The risk is considered unacceptable, and measures must be taken (to reduce the likely expected occurrence and/or severity of the consequences) until an acceptable level of risk is reached. This type of food management cannot be considered environmentally friendly in the Baltic Sea as it imposes an unacceptable burden on the DNC.				
Moderate	The risk should be reduced, if it is feasible on board, and it should meet the requirements of the MEPC.227 (64) as effectively as possible.				
Low	The risk is considered insignificant because the impact on the DNC load is negligible.				

Judgments are reviewed based on the calculated DNC_B , which consists of phosphorus and nitrogen content. This matrix also includes DNC risk tolerance criteria; namely, high/unacceptable risk, low/acceptable risk, and an average area, which is the tolerance zone between an intolerable and very probable impact of the DNC load on the Baltic Sea environment and the environment's recovery. In this context, "tolerable" refers to the type of food waste management in which the MEPC.227 (64) requirements for phosphorus and nitrogen concentrations are met.

The risk assessment of the impact of the type of food waste management on the DNC load showed that the discharging of food waste into the sea and of mixtures of shredded food waste and greywater into seawater has a high probability of producing an unacceptable or severe DNC load impact on the Baltic Sea. In addition, with mixtures of shredded food and greywater, there is a risk of introducing microplastic particles into the Baltic Sea and being a source of their distribution, the hazards of which are still under investigation. On the other hand, the level of food waste management was found to be low; i.e., the transfer of food waste management to the port, from the point of view of the Baltic Sea environment, was investigated, but the risk of the management of this waste was then transferred to the shore. Food waste sorting, storage, and incineration management have a medium level of DNC exposure due to biosafety risks: the decomposition of organic matter produces pathogens and odours dangerous to human health, and incineration is associated with CO_2 and NO_x emissions and energy efficiency.

The risk characterization of DNCs for food waste management revealed other risk groups that require further investigation.

A trend of food wastage on transport vessels was evidenced by the results of a survey analysis, which revealed a relatively wide range of wasted food.

It should be emphasized that food waste is an avoidable category of waste. Therefore, in the waste management hierarchy, one of the pillars is waste reduction [33]. Furthermore, the reduction of food waste would be associated with the improvement of society's ecological competence.

In this context, three proposals are made (see Figure 6). The first is to integrate informative content into the environmental protection training program for seafarers, which would cover not only the MARPOL 73/78 Convention regulations but also raise awareness among prospective seafarers about reducing food waste, necessity, and a change of attitude.

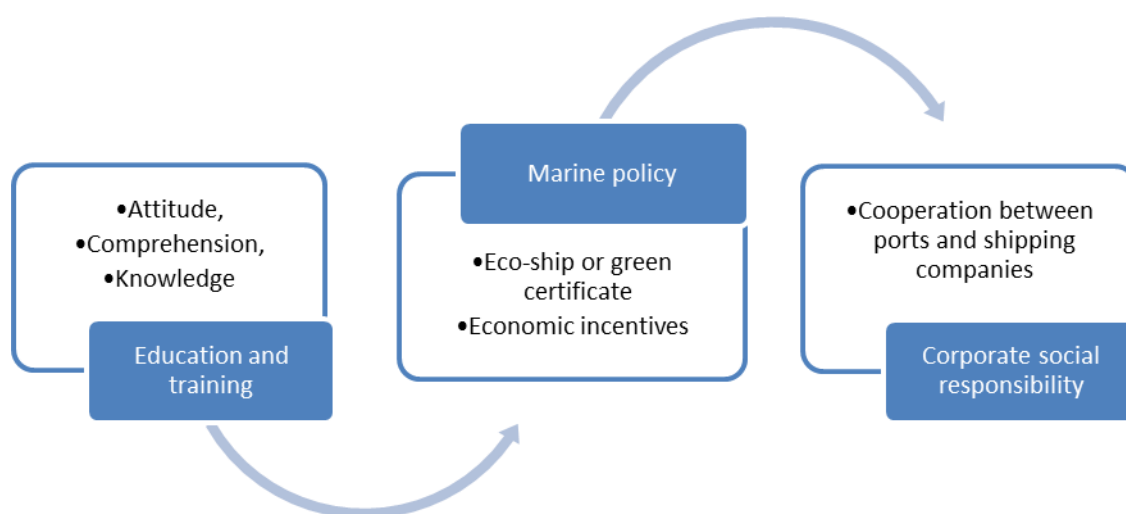


Figure 6. Proposals for the improvement of the ecological competence of society in the maritime and port sectors.

Concerning the promotion of change in marine environmental policy, acquisition of an “eco-ship” or “green” certificate reflects the set of aspects related to a ship’s high energy efficiency, low emissions, low pollution, safety, and health throughout its lifecycle. For shipowners, obtaining this certificate is stimulated by economic incentives, one of which is a reduction in port fees. However, in the context of marine pollution, it is important to include in the list of requirements for obtaining this certificate the prohibition of discharge at sea of mixtures of food waste and greywater.

A corporate social responsibility (CSR) policy based on cooperation between shipping companies and ports would stimulate the sustainable development of these two interconnected business areas.

The following pillars of the waste hierarchy relate to the reuse and recycling of organic waste, shifting it away from landfills. It should be emphasized that not all forms of land-based waste management are applicable on board ships. Therefore, it is essential to improve the systems of technological equipment already on board ships and store food waste if it is generated for various reasons. It is necessary to motivate ports to transfer food waste to shore-based recycling facilities by reducing sanitary charges for transport ships (which are several times higher than for passenger and cruise ships) or divert part of it to joint (port and shipping company CSR) development of biogas plants for alternative energy production.

In accordance with Annex IV of MARPOL 73/78, greywater is not currently regulated and does not affect the requirements for wastewater discharges into the Baltic Sea. However, drainage from ships is only permitted to those who have an approved wastewater treatment plant that meets specific nitrogen and phosphorus removal standards and is approved by the authorities [12].

Typically, wastewater treatment involves the following steps: wastewater collection, wastewater pre-treatment, wastewater oxidation, wastewater filtration (separates active biomass, sludge, and bacteria), wastewater disinfection, and finally sludge treatment [22,34]. Nutrient concentration limits are specified in the treatment standards in Annex IV of MARPOL 73/78. Membrane bioreactor (MBR) technology has recently become a popular treatment process in WWTPs. It presents excellent performance in the removal of microplastics (99.9% removal efficiency) [35].

4. Discussion

Food production volumes are a worrying aspect of the world. Despite limited resources, 30 wt.% of the food produced is lost or ruined; it becomes waste and, consequently, an additional source of pollution in the environment and a contributor to climate change. [33]. Almost 90 million tons of food is wasted in the EU every year, or an average

of 180 kg of food per capita. This accounts for about 20% of all food production and a cost of production amounting to EUR 143 billion [36]. The presented problem would be particularly interesting for the 821 million people in the world, out of the more than 7.87 billion [37], who did not have access to enough food recently [38].

The N_{Total} and P_{Total} concentrations are typically used as characterizing values in national regulations (e.g., in Latvia and Finland) for nutrient concentrations in domestic wastewater, indicated together with the chemical composition [23,39]. According to Finnish regulations, N_{Total} ranges from 48 up to 71 $\text{mg}\cdot\text{L}^{-1}$ (average 65 $\text{mg}\cdot\text{L}^{-1}$) and N_{Total} from 8.1 up to 13 $\text{mg}\cdot\text{L}^{-1}$ (average 10 $\text{mg}\cdot\text{L}^{-1}$) [23]. In turn, in Latvia, N_{Total} ranges from 20 to 100 $\text{mg}\cdot\text{L}^{-1}$ and P_{Total} from 6 to 16 $\text{mg}\cdot\text{L}^{-1}$ [39]. The maximum N_{Total} and P_{Total} reached 238 and 71 $\text{mg}\cdot\text{L}^{-1}$, respectively, in the tested greywater sample S_1 , as shown in Table 2. These values exceed nutrient limits by 2.3 (N_{Total}) and 4.4 (P_{Total}) times compared to the less restrictive values indicated for domestic water in Latvia. Also, the tested sample S_2 exhibited higher nutrient concentrations close to allowed limits for nationally regulated domestic wastewater.

The US EPA defines the regulations for the permitted chemical composition of greywater for discharge from passenger ships sailing in the Alaska region [40]. These regulations do not apply limits to nutrient concentrations but focus on BOD_5 , SSs, *F. Coli*, and Cl_2 . The permissible BOD_5 concentration is 30 $\text{mgO}_2\cdot\text{L}^{-1}$. This value is significantly (up to about 25 times) lower than those in studied the greywater samples (e.g., sample S_1 exhibited a BOD_5 of $763 \pm 76 \text{ mgO}_2\cdot\text{L}^{-1}$, see Table 2). In addition, all tested greywater samples would not have passed the allowed SS concentration tests (SSs were in the range from about 77 up to 881 $\text{mgO}_2\cdot\text{L}^{-1}$, Table 2) as they exceeded the limit defined in the US EPA (30 $\text{mgO}_2\cdot\text{L}^{-1}$). The US EPA is the only applied regulation for greywater composition we are aware of. Thus, it is necessary to draw the attention of researchers and legislators to the development, implementation, and attribution of such regulation to other types of ships in other regions as well.

The IMO supports all states' activities to achieve progress in the decarbonization path (e.g., the GreenVoyage2050 project). One of the targets is to fulfil states' commitments to meet climate-change and energy-efficiency goals in international shipping. The informative campaigns and notifications on cruise and ferry ship webpages are supported approaches aiming to attract green-thinking clients and additional investment or subsidies to their business. Shipping companies should additionally explain the wide range of synonyms applied for food waste (some of the examples are shown in Figure 3) in detail in order to clarify the sources of waste-forming substances, due to the slight differences possible in waste management methods used by different ships or companies. Such an approach would provide more significant opportunities for scientists and industry experts to carry out research and offer innovative solutions in the food waste sector, which is also one of the sources of carbon emissions. In this context, the carbon emissions relate not only to direct generation of CO_2 during waste management procedures but also energy-intensive and complex collection and removal of polluting compounds from the water as a part of environment regeneration processes for natural habitats.

Surveys of crews employed on board ships (Figure 4) seem to be one of the most effective methods currently available for checking compliance with the IMO requirements for greywater management. Unfortunately, greywater can contain plastics, glass, and other contaminants (e.g., from food packaging and reinforcing or additive materials) with long periods of degradation. Studies have revealed that those particles of plastic fragments can travel long distances from their source [41], absorb hydrophobic contaminants, and contain harmful additives—phthalates and antipyrine [42]. Importantly their decomposition can lead to release of toxic compounds. Therefore, this type of pollution should be considered a particularly significant polluting factor for environmental safety [43].

The high COD and BOD_5 in the tested greywater samples (Table 2) would cause the formation of nitrogen from dead organic matter or N-detritus in the form of ammonium ions that decompose and demineralize [24]. However, discharging nitrogen- and

phosphorus-containing greywater into the sea can potentially alter the state of local nutrients and create opportunities for algal growth, especially if one of the algae nutrients was previously absent at the site. With the possibility of algal growth, after additional nitrogen increases, the composition of the phytoplankton group changes, including a decrease in cyanobacteria, e.g., diatoms. The nitrogen cycle in the sea is dynamic. Excessively proliferating phytoplankton die due to nutrient deficiencies. N-Detritus, which binds to dead organic particles, becomes ammonia in the immediate marine environment (pH = 8.1–8.2), which oxidizes to nitrate and molecular nitrogen. The formation of these compounds results in phytoplankton rotting [44,45]. Phytoplankton (approximately 100 µm in size) may decompose faster than, for example, various shredded food wastes, the rotting time of which is determined by the food's origin [24]. As a result, oxygen consumption may be more prolonged and the potential for formation of a “dead zone” in marine waters is more significant. In 2021, more than 90 wt.% of the nitrogen and phosphorus of food waste came from passenger ships due to the large number of people being transported [31]; presently, transport vessels are a risk concern. Researchers are concerned that SSs could also contain ground food-packaging particles, such as microplastics.

The mechanical, chemical, and electrochemical [46] degradation of elements made of plastic and bare and hard-coated stainless steel, as well as many composite materials, is one of the sources of pollution in greywater. All involved sanitary facilities, screens, and pipelines are exposed to such degradation conditions. Future studies need to assess the impact of this wear on the composition of greywater and the overall potential influence on the environment.

Recently emerged and still rising demand for water purification solutions and materials has resulted in an increased number of studies aiming to develop highly efficient porous filtering products made of more durable and environmentally friendly materials [47,48]. Researchers have paid particular attention to generating porous materials using recycled materials, such as cullet from wasted window glass, old television cathode ray tubes, fluorescent lamps, and bottle glass [49]. Such materials can be reused relatively simply or recycled into new filter products. However, such an approach demands high wear and thermal resistance for structural materials in order to maintain the initial durability and filter properties in salt- and nutrient-rich (highly chemically corrosive) greywater environments. Researchers in the Baltic Sea region regard ceramics, particularly clay ceramic composites, as the best candidates for this purpose. Researchers have mainly applied industrial residues in their experiments to obtain mainly dense clay ceramic products with high chemical and mechanical resistance. However, the production of highly porous ceramic products (e.g., plates and aggregates) from such dense ceramic materials in combination with glass from municipal waste at relatively low thermal processing temperatures has not been studied systematically.

Aerobic biological treatment with the help of the activated sludge is the most commonly applied method to remove nutrients on board ships. However, researchers have recently obtained comparable performance by using portable biofilm reactors (e.g., a moving-bed biofilm reactor) [50].

5. Conclusions and Future Perspectives

This study revealed the potential risk of polluting the Baltic Sea with nutrients and other contaminants in various scenarios of “wasted” food on board ships. This may impact the marine recovery process, and proposals were made to reduce this risk.

In the first step of the risk assessment, the results of the hazard identification survey and the analysis of ship operators' websites revealed that passenger and cruise predominantly discharge food waste to PRFs for recycling. On the other hand, the management of wasted food on transport vessels is influenced by the situations in which ships end up in during voyages and by various modifications of the food waste shredder on board. Any management on board should take place without prejudice against the requirements strictly regulated by MARPOL 73/78. It was found that food waste, or a mixture of food waste

and greywater, was mainly discharged into the sea when sailing in the Baltic Sea further than 12 NM from the nearest land on the transport vessels on which the respondents were working or had worked.

In the second step of the risk assessment, hazard characterization, the results of physical/chemical tests on greywater samples from three transport vessels showed high nutrient concentrations, e.g., the S_1 sample $N_{\text{Total}} = 238 \text{ mg}\cdot\text{L}^{-1}$ and $P_{\text{Total}} = 71.00 \text{ mg}\cdot\text{L}^{-1}$, while the S_2 sample $N_{\text{Total}} = 74.5 \text{ mg}\cdot\text{L}^{-1}$ and $P_{\text{Total}} = 22.00 \text{ mg}\cdot\text{L}^{-1}$. They were more concentrated than typical municipal wastewater. The high content of organic matter in samples S_1 and S_2 indicated the presence of food waste. This was also evidenced by the COD and BOD₅ values and the high concentrations of SSs ($S_1 = 881.00 \text{ mg}\cdot\text{L}^{-1}$ and $S_2 = 335.0 \text{ mg}\cdot\text{L}^{-1}$).

In the third step of the risk assessment/exposure assessment, the estimated amounts of food waste on board transport vessels per person per day were judged to vary. On various transport vessels, the average food waste discharged into the sea was estimated to be $0.619 \text{ kg}\cdot\text{person}\cdot\text{day}^{-1}$. Mixtures of food waste and greywater discharged into the sea were estimated to amount to $0.328 \text{ kg}\cdot\text{person}\cdot\text{day}^{-1}$. Therefore, the amount estimated when both food waste management scenarios were taken into account was $0.783 \text{ kg}\cdot\text{person}\cdot\text{day}^{-1}$. The assessed amounts fall within the range of values for food waste that can be found in the small number of studies in the literature related to this topic. The amounts of these volumes are determined by the persons on board.

From the calculation of nutrient loads from the disposal of food waste at sea, based on the results of physical/chemical tests on samples, it was determined that S_1 would have contributed 155.21 g of phosphorus and 520.27 g of nitrogen. Sample S_2 would have contributed 48.09 g of phosphorus and 162.86 g of nitrogen, while S_3 would have contributed only 3.65 g of phosphorus and 2.75 g of nitrogen to the Baltic Sea. The nutrient loads of S_1 and S_2 were significant compared to the permissible feed load imposed by the MEPC.227 (64) when transport vessels discharge treated wastewater (black water or black and greywater if there are 20 persons on the ship, according to the survey results) at 56.68 g of nitrogen and 2.83 g of phosphorus.

In the fourth step of the risk assessment, risk characterization, it was revealed that discharging food waste or mixtures of food waste and greywater has a high probability of producing tolerable or unacceptable DNC load impacts on the Baltic Sea. The risk characterization of the DNC for food waste management revealed other risk groups that require further study.

Based on the results of the risk assessment, we conclude that there is a need to change the hierarchy of on-board food waste disposal regulated by MARPOL 73/78 and reduce food waste. The developed proposals are aimed at the improvement of the ecological competence of society because with increasing levels of well-being in society, the amount of food waste increases. Therefore, it is crucial to raise awareness of the need to reduce food waste already when preparing and training seafarers. Furthermore, it is essential to create tools to motivate cooperation between shipping companies and ports to recycle organic waste; for example, by using it in biogas production.

Researchers must pay additional attention to designing modern technological grey-water treatment plants to reduce environmental pollution with microplastics. In addition, developers should consider using environmentally friendly and biodegradable materials in the construction of these plants. Low-wear and recyclable materials are among the most promising options in enabling an environmentally safe circular economy in the construction and maintenance of high-performance treatment plants. The pre-treatment stage of wastewater plays an important role, requiring highly efficient porous filtration products. Therefore, we intend to perform further studies on wastewater treatment plant modernization and treating wastewater with new materials.

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