Maritime Technology and Research
https://so04.tci-thaijo.org/index.php/MTR

Research Article

Biological treatment methods of ship sewage: Case study

Ieva Demjanenko*, Renāte Kalniņa, Kristaps Lūkins and Jānis Prodnieks

Riga Technical University Latvian Maritime Academy, Flotes Str. 12 k-1, LV-1016, Riga, Latvia

Article information
Received: December 31, 2022
1st Revision: March 5, 2023
Accepted: April 7, 2023

Keywords
Ship,
Sewage treatment plant,
Biological treatment,
Moving bed biofilm reactor,
Fixed bed reactor

Abstract
The study aims to compare three sewage biological treatment methods- activated sludge, moving bed biofilm reactor (MBBR), and fixed bed biofilm reactor. The activated sludge method is the most used in ship sewage treatment. However, biofilm carrier methods, such as MBBR and fixed bed reactors, have improved in their effectiveness with industrial wastewater, with ship sewage being considered industrial. An experiment was carried out with ship untreated sewage samples, and chemical oxygen demand (COD) concentrations from different methods were analyzed and compared.

1. Introduction

Human activities have been changing the environment for centuries, which has negatively impacted the chemistry of the Earth's atmosphere and water, the rates and balance of biogeochemical processes, and the diversity of life on the planet (Cloern, 2001). Although the maritime industry has strict environmental protection policies, there are concerns about the environmental impact of operational and accidental spills from ballast, run-off, waste, and sewage (Kalnina et al., 2022). Global and governing organizations have developed various plans and regulations on how to minimize and practically measure the pollution from ships, including water and air pollution, and minimize the effects on human health and fauna. Implementation of these measures by boating and shipping operators can minimize the environmental impacts resulting from vessels are operated. However, a lack of information and monitoring has contributed to the pollution of the aquatic environment by direct discharges from ships and their crews (Byrnes & Dunn, 2020; Kalnina et al., 2021).

The International Maritime Organization (IMO) and the United Nations have implemented Sustainable Development Agenda 2030, which sets seventeen goals for sustainable development, and UN Sustainable Development Goals that relate to ship activities and water pollution elimination, includes the following: 3. good health and well-being; 6. clean water and sanitation; 7. affordable and clean energy; 9. industry, innovation and infrastructure; 13. climate action; 14. life below water (International Maritime Organization, 2019; Kalnina et al., 2021; Kalnina et al., 2022).

Ship water pollution consists of ship wastewater pollution, which can be divided into two groups: sewage or "black water" (BW), and "gray water" (GW). As it is defined in the International

*Corresponding author: Riga Technical University Latvian Maritime Academy, Flotes Str. 12 k-1, LV-1016, Riga, Latvia
E-mail address: ieva.demjanenko@gmail.com

Convention for the Prevention of Pollution from Ships (MARPOL 73/78) Technical Annex 4, sewage is wastewater and other wastes from toilets of any kind (including medical premises and spaces containing living animals), urinals or other wastes mixed with the above (International Maritime Organization, 2017; Kalnina et al., 2022). GW refers to drains from washbasins, galley sinks, showers, laundries, bathtubs, and washbasin drains, but does not include BW (International Maritime Organization, 2017), and is not yet regulated through the IMO. However, black and gray water waste streams may be mixed in the same tank; then, the regulations for black water apply (Jalkanen et al., 2020; Kalnina et al., 2021). Studies show that GW can range from 105 L per person per day to 222 L per person per day. The amount depends on vessel type, persons on board, and other variables. An average of 61 % of GW comes from the cabin area, 25 % from the kitchens, and 14 % from the laundry (Kalnina et al., 2022). The quantity of BW generated per day depends on the system onboard the ship. A vacuum system needs less water than a gravitational system, so that the amount could vary from 15 L per person per day to 102 L per day (Baltic Marine Environment Protection Commission, 2019).

For many years, ship sewage was considered the same as on land. Unfortunately, it is much more concentrated than inland wastewater, and vacuum collection systems further increases its concentration (Chen, 2022.; Kalnina et al., 2022). Sewage water pollution can be chemical, physical, and biological (Kalnina & Ivaninoka, 2020). The purification of wastewater involves using naturally occurring processes on a larger scale. On land, modern wastewater treatment systems use biological, chemical, and physical purification stages to treat wastewater due to its pollution (Baltic Marine Environment Protection Commission, 2019). These methods can be combined; common combinations are mechanical-chemical, mechanical-biological, and chemical-biological (Koboević & Kurtela, 2011).

Wastewater biological treatment methods are different, but all biochemical reactions require the presence of a biological catalyst; that is, microbial biomass or enzymes produced by microbes (Taskgroup, 2022). In biological treatment, microorganisms use impurities in the sewage as nourishment (Koboević & Kurtela, 2011). The most common method used on ships is activated sludge. Activated sludge is a traditional biological treatment using microorganisms mixed with suspended solids in the mixture to treat domestic and industrial wastewater (Tran et al., 2022). To ensure the process, oxygen has to be supplied, which can be done by diffusors or aerators (Chandra, 2016). In wastewater biochemical/biological treatment, other methods are also used- reactors and systems. Attached biofilm reactors- packed bed reactors; fluidized bed reactors; a combination of expanded bed and packed bed reactors; moving bed reactors, rely on biochemical transformations performed by a biofilm on a surface (Kalnina & Ivaninoka, 2020; Simm, 2021). Suspended growth systems- granular sludge and biofloc systems- include continuous stirred tank systems, membrane bioreactors, and activated sludge (Kalnina & Ivaninoka, 2020; Koboević & Kurtela, 2011; Koottatep et al., 2019; Simm, 2021). Also, other reactors could be used, such as fungal and electrochemical-based reactors (Simm, 2021).

To reach UN and IMO set goals, more sustainable and eco-friendly methods should be used in sewage treatment plants. Therefore, new methods should be tested.

2. Materials and methods

2.1 Experimental setup

Sterile water sample containers were prepared for sampling. Amount of samples was sufficient to ensure experimental part of the testing.

Samples were taken from a Ro/Ro vessel built in the year 1981. The sewage treatment system consisted of a holding tank and mechanical treatment technology. Sewage is not treated on this ship; it is discharged to port reception facilities due to the small passenger capacity of the ship. Therefore, this vessel was selected as the subject of the experiment as there is no sewage treatment on this vessel, only separation and grinding. Black water is mixed with gray water in one tank.

2.2 Activated sludge

A sample of 3 liters of untreated ship wastewater was mixed with 1 liter of activated sludge (see **Figure 1**), which consisted of heterotrophic bacteria, with a Sludge Density Index (SDI) of 1.2. The proportion of activated sludge and wastewater was 1:3, as recommended with mechanical aeration (see **Figure 2**) (Niaounakis & Halvadakis, 2006; Snyder & Wyant, 2010; Von Sperling, 2015).

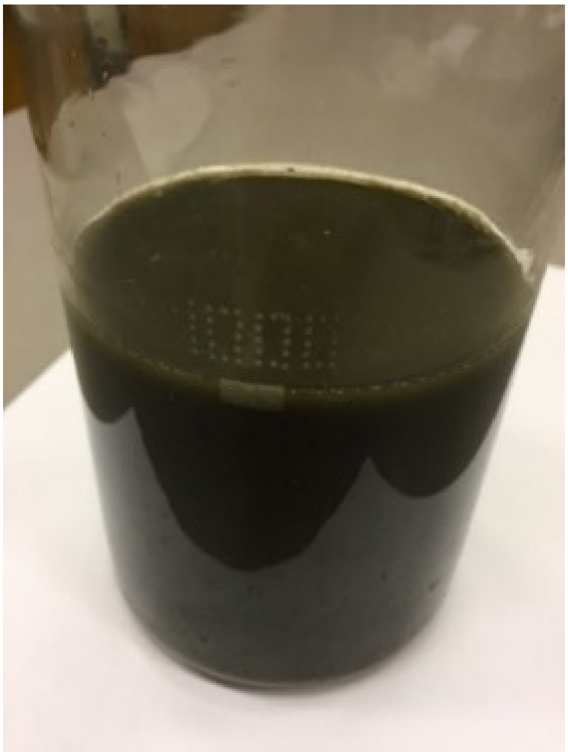

Figure 1 Activated sludge.

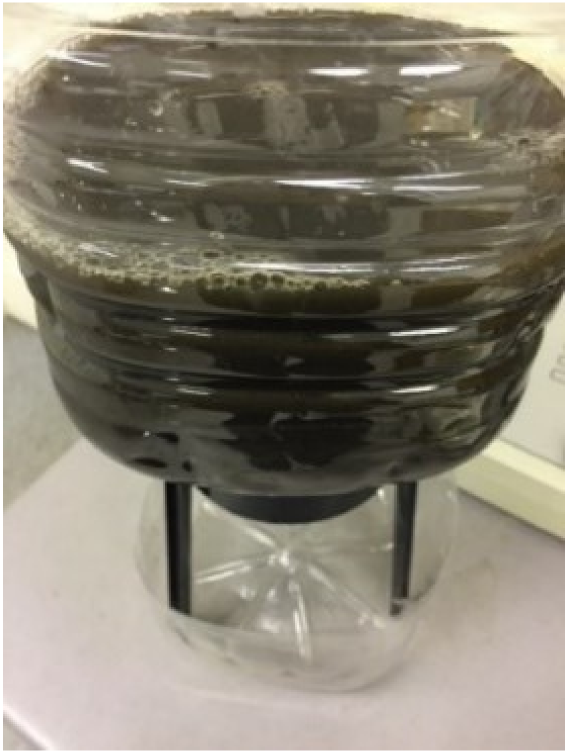

Figure 2 Activated sludge and sewage added to aeration tank.

Sewage and activated sludge were added to an aeration tank. The bioreactor worked for 24 hours, during which three samples were taken for testing- after 15 minutes, 1 hour, and 24 hours. Settling was carried out in another tank, and samples were filtered through fiberglass to remove activated sludge particles.

2.3. Moving bed biofilm reactor (MBBR)

The sewage treatment method tested was moving bed reactor and MBBR biofilm carriers, made from virgin polyethylene (PE) (see **Figure 3**). A sample of 9 liters of untreated ship wastewater was mixed with 3 liters of MBBR biofilm carriers, or approximately 170 MBBR biofilm carriers, the most suitable proportion of sewage and biofilm carriers (Al-Amshawee et al., 2020; Vieira et al., 2014).

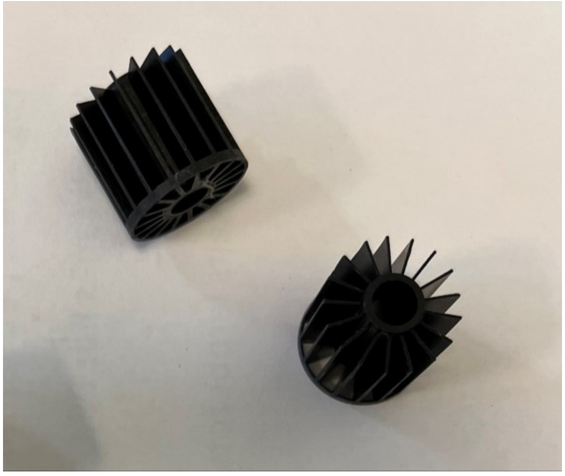

Figure 3 MBBR biofilm carrier.

Sewage and MBBR biofilm carriers (see **Figure 4**) were added to an aeration tank (see **Figure 5**). The bioreactor worked for 1 hour, during which two samples were taken for testing- after 15 minutes and 1 hour.

Figure 4 Biofilm carriers.

Figure 5 Bioreactor.

2.4. Fixed bed reactor

From 168 biofilm carriers, a cylindrical shape frame was made to fix the biofilm carriers (see **Figure 6**). The frame was attached to the bioreactor operating device. The bioreactor worked for 1 hour, during which two samples were taken for testing- after 15 minutes and 1 hour.

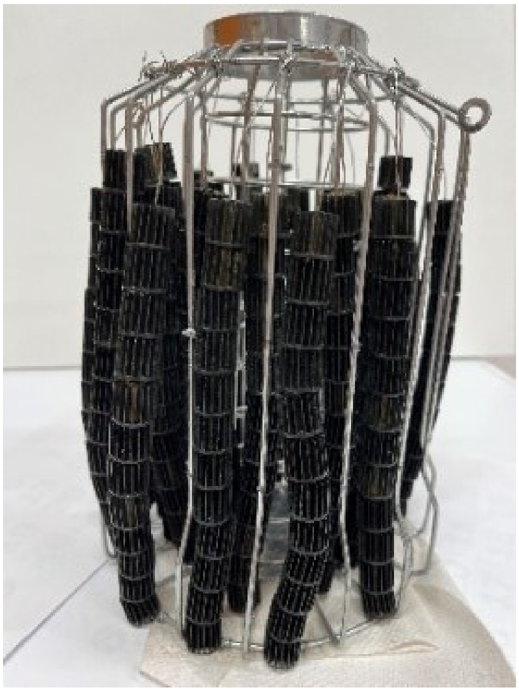

Figure 6 Biofilm carriers in cylindrical form.

2.5. Analytical methods

Samples of raw sewage and treated sewage were tested in a certified laboratory under ISO standards for wastewater pollution indicators, that is, for untreated sewage: BOD_5 (EN 1899-1:1998); suspended solid (EN 872:2007); Phosphorus (ISO 6878:2005); Nitrogen (EN

25663:2000); COD (ISO 6060:1989); and pH using pH electrodes (pH 1100 H, VWR, Germany), and for treated sewage: COD (ISO 6060:1989).

3. Results and discussion

Raw sewage samples were tested in a certified laboratory; the test results are illustrated in **Table 1**. They were compared with standards regulated by the Certificate of Type Approval for Sewage Treatment Plants (International Maritime Organization, 2012, 2022).

Table 1 Testing results and sewage treatment plant standards comparison.

Determined indicator	Untreated sewage (testing results)	Sewage treatment plant standards (MEPC 227(64))
BOD_5	150+/-15 mg/L	25 mg/L
COD	257+/-26 mg/L	125 mg/L
Coliform	N/A	100/100 mL
TSS	75.8+/-7.6 mg/L	35 mg/L
Nitrogen	1.26+/-0.10 mg/L	20 mg/L
Phosphorus	1.67+/-0.08 mg/L	1 mg/L
pH	7.4	6.0 - 8.5

Untreated sewage results showed that BOD_5 was almost 6 times higher than the standard, and COD and TSS were 2 times higher, but phosphorus exceeded the limit by only 60 %.

COD was chosen as the primary indicator to compare the biological treatment methods. COD is used to measure levels of water contamination by organic matter, which is oxidized via an oxidizing agent (potassium dichromate) (Alrumman et al., 2016). COD is one of the most widely used indicators in water quality analysis (Abba & Elkiran, 2017; Li et al., 2021; Punmia et al., 2016). COD is an imperative parameter in analyzing water parameter quality, since it provides an index to assess the impact of discharge on the receiving water body (Abba & Elkiran, 2017; Punmia et al., 2016).

The activated sludge method was tested as the most popular biological treatment method for ships wastewater treatment.

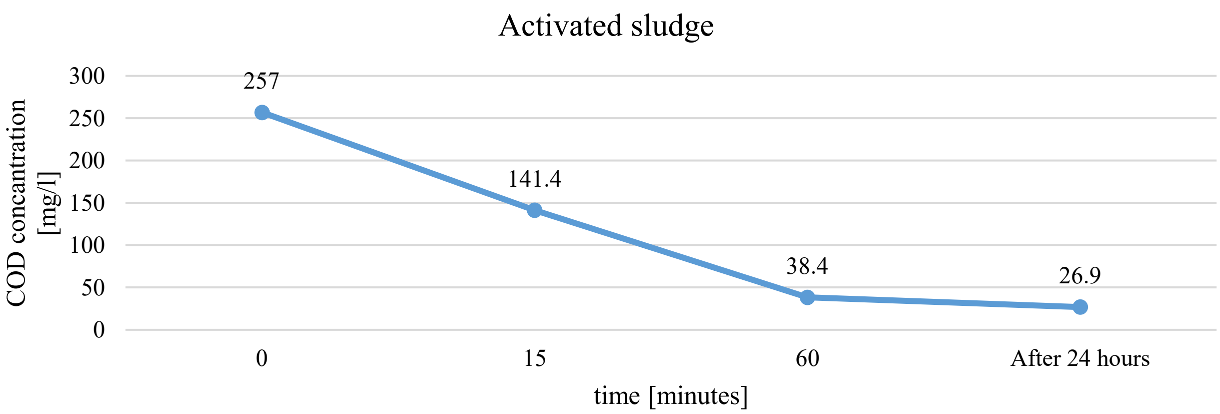

Figure 7 Activated sludge COD concentration.

The sample taken after 15 minutes (see **Figure 7**) showed that COD was 141.4 mg/L, the second sample taken after 60 minutes showed that COD was 38.4 mg/L, and after 24 hours, COD was 26.9 mg/L. Therefore, it was estimated that activated sludge effectiveness with this ship's sewage sample after 24 hours was 89.5 %, but after 1 hour, 85.1 %.

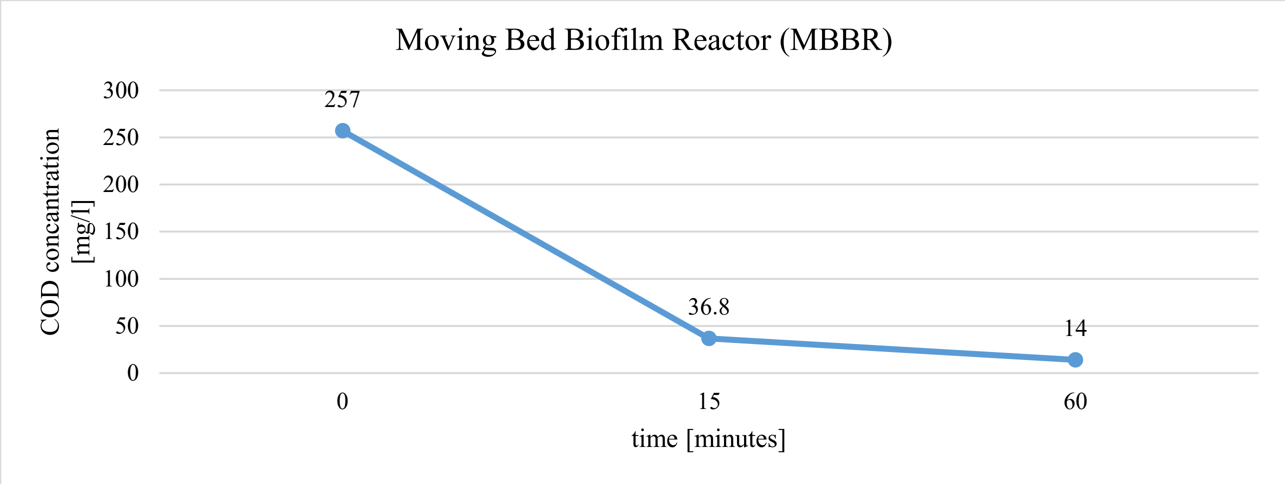

Figure 8 MBBR COD concentration.

An MBBR sample taken after 15 minutes (see **Figure 8**) showed that COD was 36.8 mg/L, but the second sample taken after 60 minutes showed that COD was 14 mg/L, which was a 94.6 % reduction of organic matter compared to the untreated sewage sample.

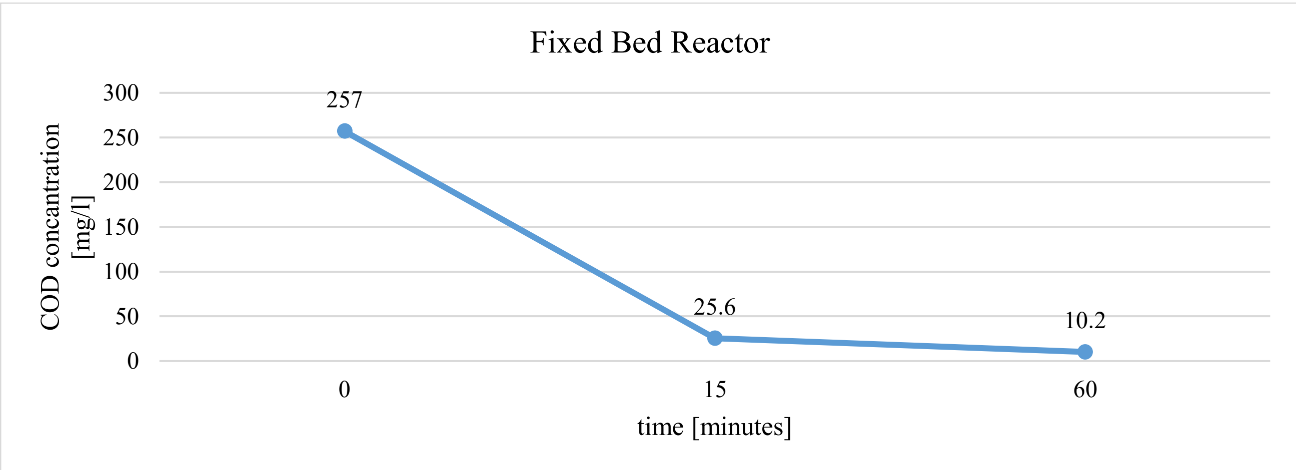

Figure 9 Fixed bed reactor COD concentration.

A fixed bed reactor sample taken after 15 minutes (see **Figure 9**) showed COD was 25.6 mg/L, but the second sample taken after 60 minutes showed that COD was 10.2 mg/L, which was a 96.0 % reduction of organic matter compared to the untreated sewage sample.

The data showed that, after 1 hour, the lowest COD concentration - 10.2 mg/L - was reached with the fixed bed reactor method. Moreover, the reduction of organic matter compared to untreated sewage was 96.0 %. The activated sludge method, the most common method on ships, presented data of COD concentration of up to 38.4 mg/L after 1 hour, or 85.1 % effectiveness compared to untreated sewage. These results indicate that the fixed bed method was more effective than the other two methods, but the MBBR method was also promising.

Not only method effectiveness should be considered when discussing ship sewage treatment. Ship sewage treatment cannot be modified on a large scale because of the system adjustment on the ships. The chosen methods that have been tested are similar to the operating principle.

The activated sludge process is a traditional biological treatment method, used for many years in ship sewage treatment plants, so this method is reliable and well-known. However, the activated sludge method should be revised, as it has disadvantages- retention time, the volume of activated sludge, and high treatment costs due to sludge disposal (Boavida-Dias et al., 2022). Also, effectiveness could be discussed compared to other methods. Sludge could be reused, for example, in biogas production in port. The energy produced in port could be used for port facilities and cargo operations, or to provide ship shore connection (Kalnina, Demjanenko, & Suraja, 2021; Kaluža et al., 2014; Wacławek et al., 2019).

The biofilm process is the best alternative to the activated sludge process. Biofilm process advantages are simple operation, its eco-friendly approach, and cost-effectiveness (Al-Amshawee et al., 2020; Kalnina & Ivaninoka, 2020). The attached biomass in the biofilm process can operate at high concentrations of active biomass (Kawan et al., 2016). The biofilm process disadvantage is that unsteady bioremediation could occur, because an ineffectively designed carrier disturbs microbial growth (Al-Amshawee et al., 2020). Therefore, the best design for ship sewage should be considered, as this can affect the performance of biological treatment.

4. Conclusions

As the results show, the best performance of biological treatment that COD indicated was with a fixed bed biofilm reactor. Comparing **Figures 8** and **9** COD concentrations, it can be assumed that the performance of these methods is more effective than the activated sludge method. Also, MBBR showed promising results. These results are consistent with those of other studies of other types of wastewater, those of the dairy, paper, phenol, and oil industries, and suggest that MBBR and fixed bed reactor are more effective methods (Madan et al., 2022; Mohd et al., 2015; Santos et al., 2020; Simm, 2021; Vieira et al., 2014).

New technologies and methods should be implemented in ship sewage treatment plants for more effective performance and to provide an eco-friendlier approach. Also, other system parts and stages should be improved, such as microplastic removal and disinfection (Kalnina et al., 2022; Kalnina & Ivaninoka, 2020), so that treated water can be used for technical purposes without creating additional waste for the environment.

Reference

Abba, S. I., & Elkiran, G. (2017). Effluent prediction of chemical oxygen demand from the wastewater treatment plant using artificial neural network application. *Procedia Computer Science*, *120*, 156-163. https://doi.org/10.1016/j.procs.2017.11.223

Al-Amshawee, S., Mohd, M. Y., & Azoddein, A. (2020). A novel microbial biofilm carrier for wastewater remediation. *IOP Conference Series: Materials Science and Engineering*, *736*, 072006. https://doi.org/10.1088/1757-899X/736/7/072006

Alrumman, S. A., El-kott, A. F., & Keshk, S. M. A. S. (2016). Water pollution: Source & Treatment. *American Journal of Environmental Engineering*, *6*(3), 88-98.

Baltic Marine Environment Protection Commission. (2019). *A technical guidance for the handling of wastewater in Ports of the Baltic Sea Special Area under MARPOL Annex IV*. Retrieved from https://helcom.fi/wp-content/uploads/2020/01/Technical-guidance-for-the-handling-of-wastewater-in-ports.pdf

Boavida-Dias, R., Silva, J. R., Santos, A. D., Martins, R. C., Castro, L. M., & Quinta-Ferreira, R. M. (2022). A comparison of biosolids production and system efficiency between activated sludge, moving bed biofilm reactor, and sequencing batch moving bed biofilm reactor in the dairy wastewater treatment. *Sustainability*, *14*(5), 5. https://doi.org/10.3390/su14052702

Byrnes, T. A., & Dunn, R. J. K. (2020). Boating- and shipping-related environmental impacts and example management measures: A review. *Journal of Marine Science and Engineering*, *8*(11), 908. https://doi.org/10.3390/jmse8110908

Chandra, R. (2016). *Environmental waste management*. CRC Press. https://doi.org/10.1201/b19243

Chen, W. (2022). *The magic of sewage treatment plant type tests*. The Maritime Executive. Retrieved from https://maritime-executive.com/corporate/the-magic-of-sewage-treatment-plant-type-tests

Cloern, J. (2001). Our evolving conceptual model of the coastal eutrophication problem. *Marine Ecology Progress Series*, *210*, 223-253. https://doi.org/10.3354/meps210223

International Maritime Organization. (2012). *Resolution MEPC227(64), 2012 Guidelines on implementation of effluent standards and performance tests for sewage plants*. International Maritime Organization.

International Maritime Organization. (2019). *Strategy, Planning and Reform. A Strategy for the IMO Secretariat to identify, analyse and address emerging issues and opportunities to further support Member States in implementing the 2030 Agenda for Sustainable Development*. International Maritime Organization. Retrieved from https://wwwcdn.imo.org/localresources/en/MediaCentre/Documents/SDG_Strategy%20and%20planning.pdf

International Maritime Organization. (2022). *Resolution MEPC.284(70), Amendments to the 2012 Guidelines on implementation of effluent standard and performance tests form sewage treatment plants (Resolution MEPC. 227(64))*. International Maritime Organization. Retrieved from https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.284(70).pdf

International Maritime Organization. (2017). *Marpol: Articles, Protocols, Annexes, Unified Interpretations of the International Convention for the Prevention of Pollution from Ships, 1973, As Modified by the Protocol of 1978 Relating Thereto*. International Maritime Organization.

Jalkanen, J. P., Johansson, L., Wilewska-Bien, M., Granhag, L., Ytreberg, E., Eriksson, K. M., Yngsell, D., Hassellöv, I. M., Magnusson, K., Raudsepp, U., Maljutenko, I., Styhre, L., Winnes, H., & Moldanova, J. (2020). *Modeling of discharges from Baltic Sea shipping*. Ocean Science. https://doi.org/10.5194/os-2020-99

Kalnina, R., & Ivaninoka, I. (2020). *Treatment methods of Ships Sewage*. In Proceeding of the 24th International Scientific Conference.

Kalnina, R., Demjanenko, I., & Suraja, K. (2021). *Perspective of sustainable shipping: Eco-ships*. In Proceedings of the 25th International Scientific Conference.

Kalnina, R., Demjanenko, I., Gorbacenko, D., Priednieks, V., & Baronins, J. (2021). Nutrient analysis of food waste from Ships' Greywater in the Baltic Sea. *Water*, *13*(17), 17. https://doi.org/10.3390/w13172421

Kalnina, R., Demjanenko, I., Smilgainis, K., Lukins, K., Bankovics, A., & Drunka, R. (2022). Microplastics in ship sewage and solutions to limit their spread: A case study. *Water*, *14*(22), 22. https://doi.org/10.3390/w14223701

Kaluža, L., Šuštaršič, M., Rutar, V., & Zupančič, G. D. (2014). The re-use of waste-activated sludge as part of a "zero-sludge" strategy for wastewater treatments in the pulp and paper industry. *Bioresource Technology*, *151*, 137-143. https://doi.org/10.1016/j.biortech.2013.10.041

Kawan, J., Abu Hasan, H., Suja, F., Jaafar, O., & Abd-Rahman, R. (2016). A review on sewage treatment and polishing using moving bed bioreactor (Mbbr). *Journal of Engineering Science and Technology, 11*(8), 1098-1120.

Koboević, Ž., & Kurtela, Ž. (2011). *Comparison of marine sewage treatment systems*. Retrieved from https://www.semanticscholar.org/paper/COMPARISON-OF-MARINE-SEWAGE-TREATMENT-SYSTEMS-1-OF-Kurtela/1e68a8c73fc62f6313a0de4674c0db52558a6cc0

Koottatep, T., Cookey, P. E., & Polprasert, C. (2019). *Technological system*. *Regenerative sanitation: A new paradigm for sanitation 4.0* (pp. 141-207). IWA Publishing. https://doi.org/10.2166/9781780409689_0141

Li, X., Wang, L., & Wang, L. (2021). Determination of chemical oxygen demand in mixed organic solution by Ti/TiO2 nanotube array electrode method. *Water Science and Technology*, *84*(4), 865-879. https://doi.org/10.2166/wst.2021.284

Madan, S., Madan, R., & Hussain, A. (2022). Advancement in biological wastewater treatment using hybrid moving bed biofilm reactor (MBBR): A review. *Applied Water Science*, *12*, 141. https://doi.org/10.1007/s13201-022-01662-y

Mohd, S. L., Mohiyaden, H. A., Basri, H., Salih, G. H. A., Birima, A. H., Ali, Z., Mohd, S. A. F., & Md. Noh, M. N. (2015). Experimental comparison between Moving Bed Biofilm Reactor (MBBR) and Conventional Activated Sludge (CAS) for river purification treatment plant. *Advanced Materials Research*, *1113*, 806-811. https://doi.org/10.4028/www.scientific.net/AMR.1113.806

Niaounakis, M., & Halvadakis, C. P. (2006). *Chapter 8-Biological processes*. *Waste Management Series* (pp. 171-218). Elsevier. https://doi.org/10.1016/S0713-2743(06)80010-3

Punmia, B. C., Jain, A. K., & Jain, A. K. (2016). *Wastewater engineering* (2nd eds.). Laxmi Publications.

Santos, A. D., Martins, R. C., Quinta-Ferreira, R. M., & Castro, L. M. (2020). Moving bed biofilm reactor (MBBR) for dairy wastewater treatment. *Energy Reports*, *6*, 340-344. https://doi.org/10.1016/j.egyr.2020.11.158

Simm, R. (2021). *Biological treatment technologies* (pp. 189-216). In Lens, P. N. L., & Pakshirajan, K. (Eds.). Environmental technologies to treat selenium pollution. IWA Publishing. https://doi.org/10.2166/9781789061055_0189

Snyder, R., & Wyant, D. (2010). *Training manual for wastewater treatment plant, operators-activated sludge process control* (pp. 1-3). Water Resources Division: State of Michigan Department of Environmental Quality.

Taskgroup. (2022). *Introduction* (pp. 1-4). In Batstone, D., & Flores-Alsina, X. (Eds.), *Generalised Physicochemical Model (PCM) for wastewater processes*. IWA Publishing. https://doi.org/10.2166/9781780409832_0001

Tran, H., Lesage, G., Lin, C., Nguyen, B., Bui, X. T., Nguyen, M., Nguyen, D. H., Hoang, H. G., Nguyen, D. D., & Minh, K. N. (2022). Activated sludge processes and recent advances. *Current Developments in Biotechnology and Bioengineering Advances in Biological Wastewater Treatment Systems, 2022*, 49-79. https://doi.org/10.1016/B978-0-323-99874-1.00021-X

Vieira, D., Oliveira, M., Dias, R. M., Nariyoshi, Y., & Nascimento, Y. (2014). Evaluation of a MBBR (moving bed biofilm reactor) pilot plant for treatment of pulp and paper mill wastewater Evaluation of a MBBR (Moving Bed Biofilm Reactor) pilot plant for treatment of pulp and paper. *International Journal of Environmental Monitoring and Analysis*, *2*, 220-225. https://doi.org/10.11648/j.ijema.20140204.15

Von Sperling, M. (2015). *Activated sludge and aerobic biofilm reactors*. Water Intelligence Online, IWA Publishing. https://doi.org/10.2166/9781780402123

Wacławek, S., Grübel, K., Silvestri, D., Padil, V. V. T., Wacławek, M., Černík, M., & Varma, R. S. (2019). Disintegration of Wastewater Activated Sludge (WAS) for improved biogas production. *Energies*, *12*(1), 21. https://doi.org/10.3390/en12010021