JIP
Jurnal Ilmiah PLATAX
Universitas Sam Ratulangi
Terakreditasi Ristekdikti No: 28/E/KPT/2019
ISSN : 2302-3589 (Online)
E_mail : jm_platax@unsrat.ac.id

Ship Maintenance Techniques for Removing Sea Barnacles That Stick to The Ship's Hull

Haryadi Wijaya*, Lucia Ingrid Regina Lefrandt, Charles Stanley C Punuhsingon

Engineer Professional Program Study Program (PPI) at Sam Ratulangi University
e-mail: haryadi.wijaya.hw@hmail.com

Manuscript received: 10 Mar. 2025. Revision accepted: 4 April. 2025

Abstract

This research aims to analyze the effectiveness of various ship maintenance techniques in removing sea barnacles and evaluate the advantages and challenges of each method used. The research method employed is a Systematic Literature Review (SLR), which analyzes various previous studies that discuss ship maintenance techniques for preventing and eliminating fouling. Data analysis was conducted using NVivo to identify research trends and VOSviewer to map relationships between the methods used in previous studies. The research results show that the most effective approach in preventing the growth of barnacles is a combination of several methods, such as the use of silicone or fluorine-based paint which has low adhesion, ultrasonic technology which inhibits the colonization of marine biota, and a robot-based automatic cleaning system which can remove fouling without damaging the structure of the ship. This hybrid approach not only enhances the fuel efficiency of ships but also helps mitigate the impact of marine pollution caused by the use of toxic chemicals. With the development of antifouling technology and more innovative maintenance strategies, the shipping industry is expected to increase operational efficiency while supporting the long-term sustainability of the marine environment.

Keywords: Ship Treatment, Antifouling, Ultrasonic Technology, Fouling, Hybrid Approach.

INTRODUCTION

Empirical data show that ships experiencing the accumulation of barnacles and other marine biota can experience an increase in hydrodynamic resistance of up to 40%, resulting in an increase in fuel consumption of 15-20% under the same operating conditions [1]. In addition, the increasing maintenance costs and frequency of manual cleaning also add to the operational burden and disrupt shipping schedules, forcing stakeholders to seek innovative solutions that not only address technical issues but also have a positive impact on economic and environmental efficiency.

Various ship maintenance materials and technologies have been developed to address these issues starting with the application of chemical-based antifouling coatings designed to inhibit the growth of marine organisms on the hull surface [2]. This innovation is balanced with research on the composition of more environmentally friendly materials, in order to reduce the impact of toxicity that may be caused by these chemicals on the aquatic ecosystem. The development of modern paint and coating technology is one of the mainstays in optimizing the protection of the ship's hull while maintaining its beauty and structural integrity.

Mechanical and non-chemical techniques such as high-pressure water cleaning, the use of ultrasonic technology, and automated cleaning systems have been tested as more efficient and sustainable alternatives. These techniques not only reduce the reliance on chemicals but also allow maintenance processes to be carried out in a shorter time and at a relatively lower cost. The integration of mechanical and chemical approaches in ship maintenance offers a holistic solution that can be tailored to the operational conditions and characteristics of a particular ship [3].

Innovative technologies and methods in ship maintenance continue to develop along with research progress and industry needs. Various experimental and field studies have shown that the combination of advanced materials, proper application techniques, and real-time monitoring systems can improve cleaning effectiveness and extend the life of ship hull protection. Collaborative efforts between researchers, engineers, and industry practitioners are key to developing maintenance techniques that not only improve ship performance but also contribute to marine environmental conservation efforts.

The purpose of this study is to evaluate and optimize ship maintenance techniques in removing marine barnacles attached to the ship's hull through an integrated approach so that it is expected to reduce hydrodynamic resistance, increase fuel efficiency, and reduce negative impacts on the marine environment. This study aims to identify the best method that can be widely applied in the shipping industry while providing strategic recommendations for the development of ship maintenance technology in the future.

RESEARCH METHODS

The research method used in this study is the Systematic Literature Review (SLR), where researchers systematically identify, collect, and analyze literature related to ship maintenance techniques in removing sea barnacles attached to ship hulls [4]. The SLR process begins with the formulation of a search strategy that includes determining keywords, selecting leading databases such as Scopus, Web of Science, and Google Scholar, and applying inclusion and exclusion criteria to filter relevant articles. Each literature that meets the criteria is then critically evaluated to assess its methodological quality and contribution to the understanding of ship maintenance problems [5]. These steps ensure that the data obtained is accurate, and up-to-date, and can support in-depth analysis of the various approaches and solutions that have been implemented in addressing the buildup of marine barnacles on ship hulls.

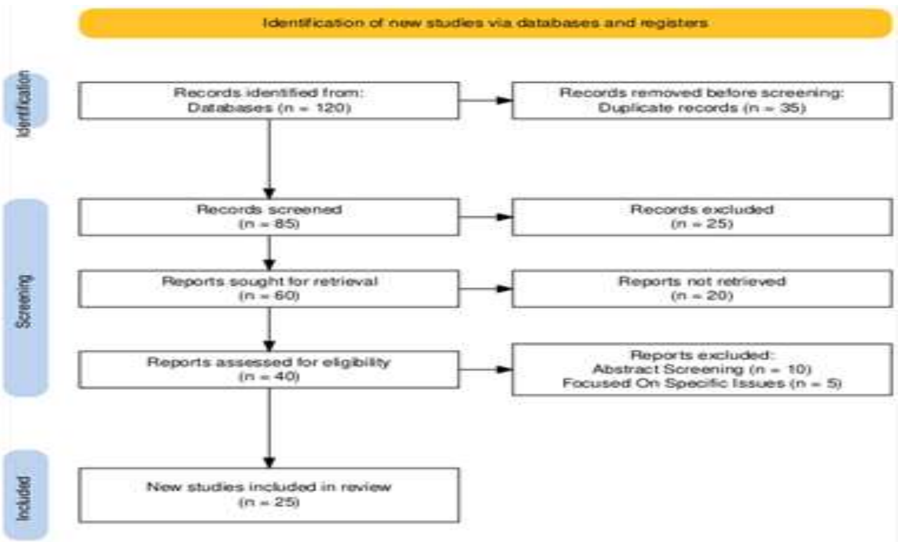

Figure 1. Prisma table

Data analysis was conducted by integrating two analysis tools, namely NVivo and VOSviewer, to provide a holistic and comprehensive picture. NVivo is used for qualitative analysis, especially in coding and categorizing findings from selected literature, thus facilitating the identification of key themes, research trends, and gaps that still need to be addressed in the field of ship maintenance [6]. Meanwhile, VOSviewer is used for bibliometric analysis and network visualization, such as maps of collaboration between authors, relationships between keywords, and distribution of publications over time. The integration of the two analysis tools allows researchers to present data in a structured and visual way and supports evidence-based decision-making in developing more efficient and sustainable ship maintenance techniques.

Figure 1 shows the study selection process flow using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, starting from the identification stage to the studies that were finally included in the review. In the initial stage, 120 articles were identified from various databases, and then 35 of them were removed due to duplication. Next, the remaining 85 articles underwent an initial screening process, which left 60 articles for further review. However, 20 articles were inaccessible or not available in full text, so only 40 articles were evaluated for eligibility. Of these, 15 articles were excluded for certain reasons (10 of them due to abstract limitations and 5 others were too specific or irrelevant), leaving 25 articles that were deemed eligible and finally included in this systematic review. Thus, the PRISMA flow helps ensure that the study selection process is transparent, structured, and accountable [7].

RESEARCH RESULT

Research on ship maintenance techniques in removing sea barnacles attached to the ship's hull has been widely conducted by academics and maritime practitioners. One of the most commonly used methods is the application of antifouling coatings, which aims to reduce or prevent the growth of marine biota on the surface of the ship's hull. According to research conducted by [8], copper-based antifouling paint was able to reduce the growth rate of barnacles by up to 80% within six months of use. However, another study conducted by [9] showed that although copper-based paint is effective in preventing barnacle growth, its long-term use can cause heavy metal pollution in the marine environment, which is harmful to the ecosystem. This is also supported by a study conducted by [10], who found that copper waste produced from antifouling paint can reduce water quality and disrupt the balance of the aquatic ecosystem around the port.

As an alternative to copper-based paints, some studies have explored the use of silicone or fluorine-based antifouling paints, which are more environmentally friendly. [11] his research revealed that silicone-based paint has a high-release effect, where the surface of the ship's hull becomes more slippery and reduces the adhesion of barnacles. This study is also supported by the findings [12], which show that the use of silicone paint can reduce ship drag by up to 15%, thus impacting fuel efficiency. In addition, research by [13] found that fluorine-based paints also have good antifouling properties, especially in environments with high exposure to marine life, due to their ability to inhibit barnacle attachment through a self-cleaning mechanism.

Mechanical methods such as manual and automated cleaning are also still used in the shipping industry to remove marine barnacles from ship hulls. [14] stated that manual cleaning methods using brushes or scrapers are still the main choice for many small ship operators, especially because of their relatively low cost. Research by [15] showed that this method takes a long time and has the risk of damaging the antifouling paint layer, which in turn accelerates the regrowth of barnacles. Research conducted by [16] recommends the use of automated robotic systems capable of cleaning ship hulls without damaging the surface. This technology has been proven to increase cleaning effectiveness by up to 40% compared to manual methods, although it has a fairly high initial investment cost.

Ultrasonic technology is also starting to be developed as an innovative method to inhibit the growth of barnacles on ship hulls. [17] in his research revealed that ultrasonic waves with certain frequencies can disrupt the initial adhesion process of barnacles, thus preventing further growth. This study is also supported by research [18], which found that vessels equipped with ultrasonic systems experienced a 70% reduction in barnacle growth over six months. However, research by [19] shows that the effectiveness of ultrasonic technology is highly dependent on the intensity and frequency of the waves used, as well as the design of the system applied. If not configured properly, the effect can be suboptimal, especially for vessels that frequently operate in waters with high levels of marine biota growth.

Several studies have proposed hybrid approaches that combine more than one method to enhance the effectiveness of ship treatments in removing barnacles. [20] in his study showed that the combination of silicone-based antifouling paint with an automatic cleaning system can significantly reduce ship drag and increase fuel efficiency by up to 15%. Another study by[21]found that by applying a hybrid approach combining fluorine-based paint and ultrasonic technology, ships can maintain a clean hull condition longer than using either method alone. This is in line with research by[22], which revealed that this multimodal approach was able to reduce the frequency of manual cleaning by up to 50%, thereby reducing ship operating costs in the long term.

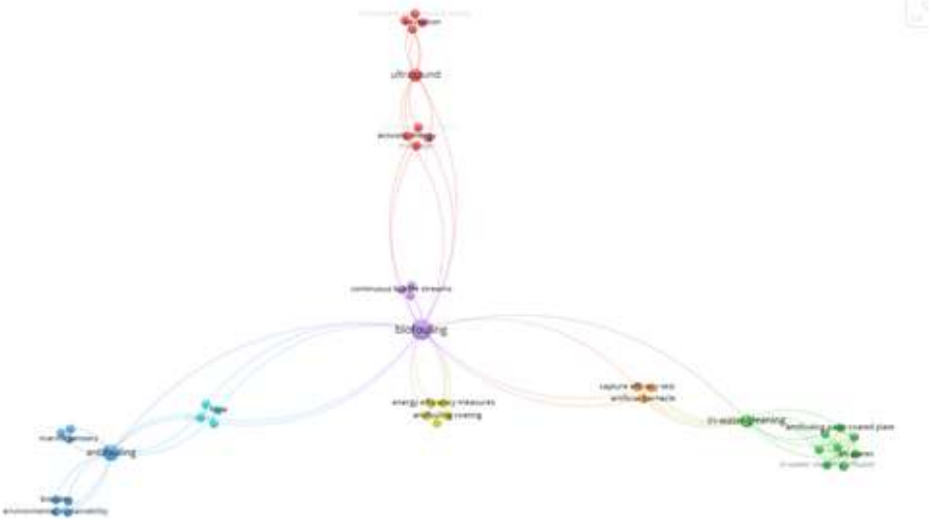

Figure 2. Analysis of Previous Study Grouping Through VOSviewer.

Figure 2 shows the results of the clustering analysis of previous studies on ship maintenance techniques for removing marine barnacles using VOSviewer. This visual map groups key concepts in biofouling research based on the interrelationships between topics that are often discussed together in the literature. It can be seen that biofouling is the main center that connects several ship maintenance approaches, such as antifouling coatings, ultrasonics, and in-water cleaning. Ultrasonic technology is presented as one of the innovative methods in biofouling prevention, with related concepts such as cavitation, acoustic energy, and multiwaves showing how ultrasonic waves work to disrupt the adhesion of marine biota. On the other hand, the antifouling group shows its relationship with the concepts of biocides, sustainability, and marine sensors, indicating that this method still relies on certain chemicals, but is also increasingly directed towards a more environmentally friendly approach. In-water cleaning is a separate group that includes mechanical techniques for removing biofouling without the need for docking, with related concepts such as antifouling paint-coated plates, cleaning effluents, and AFC plates that illustrate the efficiency of these methods in cleaning the hull without damaging the antifouling layer. In addition, energy efficiency-based approaches and capture efficacy tests are also part of this study, demonstrating that fouling prevention and removal methods must consider their impact on the overall performance of the ship. This map confirms that the best strategy in ship maintenance is a multimodal approach that combines antifouling methods, ultrasonic technology, and mechanical cleaning to achieve optimal efficiency in preventing barnacle growth on the hull.

Overall, the discussion of the results of this study reveals that there is no single method that is superior in removing barnacles from ship hulls. Each technique has its own advantages and disadvantages, depending on the operational conditions of the ship, maintenance budget, and applicable environmental regulations. Chemical-based methods such as antifouling paint are still the main solution but are starting to be challenged by increasingly stringent environmental regulations. Meanwhile, mechanical and ultrasonic methods offer more sustainable alternatives, although with their own challenges in terms of effectiveness and implementation costs. Considering the findings of various previous studies, the most optimal approach in preventing and removing barnacles from ship hulls is an integrated approach, which combines various techniques according to the specific needs of the ship and its operational conditions.

DISCUSSION

A. Effectiveness of Antifouling Coating in Inhibiting Barnacle Growth

The growth of marine life on ship hulls is a serious problem in the maritime industry. One of the organisms that most often attach to ship hulls is barnacles. The presence of barnacles not only causes increased hydrodynamic drag that slows down the ship's speed but also increases fuel consumption because the ship requires more power to move. In addition, the accumulation of marine organisms on the ship's hull can accelerate corrosion and reduce the operational life of the ship. To overcome this problem, various methods have been developed, one of which is the use of antifouling coatings.

The antifouling coating is a technology applied to ship hulls to inhibit the growth of marine biota by various mechanisms, ranging from the release of chemicals that are toxic to marine organisms to the use of materials that physically inhibit the adhesion of biota. This method has been widely applied because it is considered an efficient and durable solution in preventing fouling. However, the effectiveness of each type of coating depends on various factors, including environmental conditions, duration of use, and the technology used in the paint formulation.

As technology advances and environmental regulations become more stringent, the shipping industry is shifting from traditional toxic-based methods to more environmentally friendly alternatives. Therefore, it is important to understand the effectiveness of the various types of antifouling coatings available and the advantages and challenges faced in their implementation. Antifouling coatings can be categorized into several types based on their mechanism of action. The three main types commonly used are copper-based paints, silicone-based paints, and fluorine-based paints [23]:

1. Copper Based Paint

Copper-based paints work by releasing copper ions into the water, creating an inhospitable environment for marine life to grow. Compounds such as copper oxide and copper thiocyanate are often used in the formulation of these paints because they have a strong biocidal effect on marine organisms. The main advantage of this paint is its high effectiveness in preventing fouling, so it is widely used on commercial and military ships.

Although very effective, the use of copper-based paint has a significant environmental impact. Copper ions released into the water can cause pollution and disrupt the balance of the marine ecosystem. Large amounts of copper accumulation can be toxic to plankton, mollusks, and other marine organisms, which can ultimately disrupt the food chain in the water. Several countries have begun to limit or even ban the use of copper-based paint to maintain the sustainability of the marine ecosystem.

2. Silicone Based Paint

As a more environmentally friendly alternative, silicone-based paints were developed on the principle of creating a very slippery surface that makes it difficult for marine organisms to stick to it. The silicone coating reduces the adhesion of marine life and allows it to be easily removed when the ship is moving. In addition, silicone paints do not contain toxic materials, making them safer for the environment than copper-based paints. Another advantage of silicone-based paints is their ability to reduce friction between the ship's hull and the water, thereby increasing fuel efficiency. With reduced hydrodynamic drag, ships can sail faster with less fuel consumption. However, this paint has a disadvantage in terms of durability. Silicone coatings tend to degrade more quickly and require regular maintenance to remain effective.

3. Fluorine Based Paint

Fluorine-based paints work by creating a super-hydrophobic layer that inhibits the attachment of marine organisms. Unlike silicone, which only reduces adhesion, fluorine paints have self-cleaning properties, where marine biota that adhere will automatically be released from the ship's surface. The main advantage of fluorine-based paints is their longer durability compared to silicone-based paints. However, the production and application costs of fluorine paints are still relatively high, so their use is not as popular as copper and silicone-based paints. In some cases, this coating is more suitable for ships operating in waters with high levels of marine biota growth, where the effectiveness of conventional methods is less than optimal.

The effectiveness of antifouling coatings is highly dependent on several interacting factors. The main factors that influence the performance of these coatings include [24]:

1. Water Conditions

Waters with high temperatures and high nutrient levels tend to have faster marine biota growth rates, requiring more durable and effective coatings. In addition, the salinity and oxygen content of the water also affect the resistance of the coating to corrosion and degradation.

2. Ship Operational Frequency and Speed

Ships that frequently sail at high speeds experience less barnacle growth than ships that frequently dock or operate at low speeds. The movement of the ship helps prevent marine organisms from attaching, thus maximizing the effectiveness of the antifouling coating.

3. Paint Durability and Resistance

Each type of coating has a different level of resistance to marine environments. Silicone-based paints, for example, degrade more quickly than copper-based paints, requiring more frequent reapplication.

4. Application and Maintenance Methods

The way the coating is applied also affects its effectiveness. Uneven or substandard application can reduce the durability of the paint and increase the possibility of fouling. In addition, regular maintenance is essential to ensure the coating remains effective in the long term.

The shipping industry continues to innovate in more effective and environmentally friendly antifouling technologies as environmental regulations increase. One of the latest innovations is nanotechnology-based paints that inhibit the adhesion of marine organisms without the use of toxic chemicals, although it is still in the development stage. A hybrid approach that combines antifouling coatings with ultrasonic technology and automatic cleaning is being implemented to increase the effectiveness of antifouling systems, extend the life of the paint, and reduce the frequency of maintenance. In the future, the maritime industry is expected to shift to more environmentally friendly antifouling technologies with stricter regulations on toxic materials. With continued innovation, antifouling technology is expected to continue to adapt to industry needs, maintain ship hull cleanliness, and improve operational efficiency without damaging marine ecosystems.

B. Mechanical Methods in Manual and Automatic Barnacle Removal

The shipping industry faces a major challenge in dealing with the growth of marine biota attached to the hull of ships, especially barnacles. The accumulation of these organisms can cause various operational problems, ranging from increased hydrodynamic resistance to increased fuel consumption. Along with that, the operational costs of ships become higher, while shipping efficiency decreases significantly. To overcome this problem, various methods have been developed, one of which is the mechanical method of removing barnacles, both manually and automatically.

Mechanical methods in ship maintenance aim to remove marine life from the hull of the ship by physical means. This approach is different from chemical methods, such as antifouling paints that contain toxic materials to prevent the adhesion of marine organisms. Mechanical methods are divided into two main categories, namely manual cleaning, which is carried out conventionally using simple tools such as brushes or scrapers, and automatic cleaning, which uses modern technology such as hull cleaning robots and ultrasonic-based systems [25].

Manual and automatic mechanical cleaning have their own advantages and disadvantages. The manual method is simpler and cheaper but requires a large workforce and longer time. Meanwhile, the automatic method is more efficient in the long term and is able to clean hard-to-reach areas, but requires a fairly high initial investment cost. With the development of technology, the maritime industry has begun to adopt an automated approach in an effort to improve the effectiveness of ship maintenance. However, the effectiveness of these two methods is still influenced by various factors, including the condition of the water environment, ship design, and the frequency of maintenance carried out.

Manual cleaning is the oldest mechanical method of removing barnacles from a ship's hull. This method has been used since ancient times and is still widely used today, especially on small ships or ships operating in areas with limited access to modern technology. Manual cleaning is done using simple tools such as wire brushes, scrapers, or high-pressure cleaning tools. This method is usually carried out when the ship is docked at a shipyard, where the bottom of the ship can be easily accessed. The process involves workers scrubbing or scraping off marine life that sticks to the ship's hull, so that the surface of the ship is clean again and ready for use again.

Although classified as a conventional method, manual cleaning still has several advantages. One of the main advantages is the relatively low cost. Because this method does not require high-tech equipment, the initial investment required is also smaller than the automatic method. In addition, this method allows for selective cleaning, where only certain parts that experience severe marine biota growth are cleaned, thus saving time and energy [26]. The manual method is also more flexible in its application, because it can be done at any time without the need to use complicated technology. On small ships, this method is often the main choice because it is more practical than using sophisticated technology. In addition, the manual method can be combined with other methods, such as applying antifouling paint after the cleaning process is complete, to increase effectiveness in preventing barnacle growth again.

Manual hull cleaning methods have several disadvantages, such as requiring a lot of time and labor, the risk of damaging the antifouling layer, and the potential danger to workers. Therefore, the shipping industry has begun to switch to more efficient and safe automated cleaning methods, such as the use of cleaning robots, high-pressure water, and ultrasonic technology. Cleaning robots are able to work continuously with high efficiency without damaging the antifouling layer, while high-pressure water systems can remove fouling quickly even though they pose a risk to the hull structure. In addition, ultrasonic technology offers a fouling prevention solution without physical cleaning, although its effectiveness still needs to be further studied. Overall, although automated methods have high initial investment costs, their advantages in efficiency, safety, and environmental protection make them the main choice in the modern shipping industry.

CONCLUSION

Ship maintenance techniques for removing barnacles have evolved from conventional methods such as antifouling coatings to ultrasonic-based innovations and hybrid approaches to improve efficiency and reduce environmental impact. Although copper-based antifouling paints are effective, their impact on marine ecosystems has prompted the development of alternatives such as silicone and fluorine coatings, which are more environmentally friendly but still face challenges in terms of effectiveness and durability. Mechanical methods, both manual and automated, are still used, despite their cost limitations and the risk of damage to the ship's hull. Ultrasonic technology offers an innovative solution by disrupting the adhesion of marine biota, although its effectiveness still depends on environmental conditions and system configuration. Therefore, hybrid approaches that combine different methods are increasingly being applied to maintain ship hull cleanliness sustainably. To improve effectiveness, the choice of method must be tailored to the needs of the ship, a combination of chemical and mechanical techniques needs to be developed, shipping regulations must support more environmentally friendly antifouling technologies and investment in nanotechnology and artificial intelligence research and development needs to be increased. With more innovative strategies, the maritime industry can improve operational efficiency, reduce fuel consumption, and contribute to marine environmental sustainability.

ACKNOWLEDGMENTS

The writing of this article was submitted for completing the Engineer Professional Program at the Graduate School of Sam Ratulangi University Manado. The writing of this article can be completed because of help and suggestions from various parties. For this Opportunity, we would like to express our highest gratitude and appreciation to: 1. Dr. Ir. Lucia I. R. Lefrandt, ST., MT., IPU., ASEAN.Eng. as the First Supervisor of the Postgraduate Engineer Professional Program (PPI) of Sam Ratulangi University who provided a lot of advice in completing this task, 2. Dr. Eng. Ir. Charles S.C. Punuhsingon, S.T., M.T., IPM, ASEAN Eng. as the Second Supervisor of the Postgraduate Engineer Professional Program (PPI) of Sam Ratulangi University, who provided a lot of advice in completing this task, 3. Dr. Ir. Lucia I. R. Lefrandt, ST., MT., IPU., ASEAN. Eng. as the Coordinator of the Engineer Professional Program Study Program at Sam Ratulangi University, who guided to complete Batch XXII of the Engineer Professional Program at Sam Ratulangi University Manado. 4. Prof. Dr. Ir. Oktovian Berty A. Sompie, M.Eng., IPU., ASEAN Eng as the Rector of Sam Ratulangi University Manado, who has provided the opportunity to complete the Engineer Professional Program of Sam Ratulangi University Manado, 5. Prof. Dr. Ir. Markus T. Lasut, M.Sc., IPU as the Director of Postgraduate Studies at Sam Ratulangi University Manado, Prof. Dr. Ir. Johannes E.X. Rogi, M.Si as Deputy Director I, and Dr. Eng. Ir. Steeva Gaily Rondonuwu, ST., M.Agr as Deputy Director II, who have provided the opportunity to complete professional education in the Engineer Professional Program Study Program, Sam Ratulangi University, Manado. We certify that there is no conflict of interest with any organization regarding the materials discussed in this manuscript.

REFERENCE

[1] NN Pereira, "Continuous air Bubbles Application in Guanabara Bay to Avoid the Marine Biofouling in Stationary," *Preprint*, vol. 11, no. 2, pp. 76–84, 2020.

[2] A. Vanangamudi and S. Punniyakoti, "The anti-fouling activity of solvothermally synthesized Nb2O5-coated Fe ship strip on optimal interactions at the targeted interfaces of barnacle attachments -An Insilico study," *Mater. Res. Express*, vol. 11, no. 11, 2024, doi: 10.1088/2053-1591/ad8eac.

[3] G. Rk, J. Harshavardini, P. Nivethaa, and KME Nandini, “BioBlitz Bot: A Comparative Analysis of Cleaning Efficiency in Marine Environments,” *J. Curr. Res. Eng.*, vol. 7, no. 1, pp. 1–8, 2024.

[4] RM Muhammad Umam Mubarok, Maheni Ika Sari, Yohanes Gunawan Wibowo, "Comparative Study of Artificial Intelligence (AI) Utilization in Digital Marketing Strategies Between Developed and Developing Countries: A Systematic Literature Review,"*Ilomata Int. J. Manag.*, vol. 6, no. 1, pp. 156–173, 2025, doi: 10.61194/ijjm.v.6i1.1534.

[5] J. Creswell, “Qualitative Inquiry Research Design Choosing Among FiveApproaches.” 2017.

[6] JW Creswell and JD Creswell, *Mixed Methods Procedures*. 2018.

[7] NR Haddaway, MJ Page, CC Pritchard, and LA McGuinness, “PRISMA2020: An R package and Shiny app for producing PRISMA 2020-compliant flow diagrams, with interactivity for optimized digital transparency and Open Synthesis,” *Campbell Syst. Rev.*, vol. 18, no. 2, p. e1230, Jun. 2022, doi: https://doi.org/10.1002/cl2.1230.

[8] M. Lagerstrom, “Investigation of critical copper release rates for dose optimization of antifouling coatings,” Prog. Org. Coatings, vol. 198, no. November 2024, 2025, doi: 10.1016/j.porgcoat.2024.108928.

[9] F. Cima and R. Varello, "Potential disruptive effects of copper-based antifouling paints on the biodiversity of coastal macrofouling communities, "*Environ. Sci. Pollut. Res.*, vol. 2, no. 2, pp. 1–25, 2022, doi: 10.1007/s11356-021-17940-2.

[10] H. Carić, N. Cukrov, and D. Omanović, “Nautical tourism in marine protected areas (Maps): Evaluating an impact of copper emissions from antifouling coating,” *Sustain.*, vol. 13, no. 21, 2021, doi: 10.3390/su132111897.

[11] Z. Cao and P. Cao, “Research Progress on Low-Surface-Energy Antifouling Coatings for Ship Hulls: A Review,” *Biomimetics*, vol. 8, no. 6, pp. 1–14, 2023, doi: 10.3390/biomimetics8060502.

[12] DR Oliveira, M. Lagerström, L. Granhag, S. Werner, AI Larsson, and E. Ytreberg, “A novel tool for cost and emission reduction related to ship underwater hull maintenance,”*J. Clean. Prod.*, vol. 356, no. April, 2022, doi: 10.1016/j.jclepro.2022.131882.

[13] I. Ielo, F. Giacobello, A. Castellano, S. Sfameni, G. Rando, and M.R. Plutino, “Development of Antibacterial and Antifouling Innovative and Eco-Sustainable Sol-Gel Based Materials: From Marine Areas Protection to Healthcare Applications,” *Gel*, vol. 8, no. 1, 2022, doi: 10.3390/gels8010026.

[14] F. Nauert and P. Kampmann, “Inspection and maintenance of industrial infrastructure with autonomous underwater robots,” *Front. Robot. AI*, vol. 10, no. August, pp. 1–20, 2023, doi: 10.3389/frobt.2023.1240276.

[15] B. Donnelly, K. Sammut, and Y. Tang, “Materials Selection for Antifouling Systems in Marine Structures,” *Molecules*, vol. 27, no. 11, 2022, doi: 10.3390/molecules27113408.

[16] K. Wei, Z. Zhang, and Z. Zhou, “Design of a new composite underwater hull cleaning robot,” *J. Sea Res.*, vol. 198, no. January, p. 102488, 2024, doi: 10.1016/j.seares.2024.102488.

[17] H. Kuşku, “Effects of Exposure Time of Sonication on Physical Dispersal of Mucilage: A Preliminary Study,” *J. Eng. Technol. Appl. Sci.*, vol. 7, no. 1, pp. 31–44, 2022, doi: 10.30931/jetas.1034671.

[18] YA Mehanna, E. Sadler, R.L. Upton, AG Kempchinsky, Y. Lu, and CR Crick, “The challenges, achievements, and applications of submersible superhydrophobic materials,” *Chem. Soc. Rev.*, vol. 50,

no. 11, pp. 6569–6612, 2021, doi: 10.1039/d0cs01056a.
[19] T. Muhayat, “Smartphone Price Prediction Using Multiple Linear Regression Algorithm,” *Thesis*, 2022, [Online]. Available: http://link.springer.com/10.1007/s00232-014-9701-9%0Ahttp://link.springer.com/10.1007/s00232-014-9700-x%0Ahttp://dx.doi.org/10.1016/j.jmr.2008.11.017%0Ahttp://linkinghub.elsevier.com/retrieve/pii/S1090780708003674%0Ahttp://www.ncbi.nlm.nih.gov/pubmed/1191
[20] S. Wu*et al.*, “Research Progress of Marine Anti-Fouling Coatings,” Coatings, vol. 14, no. 9, 2024, doi: 10.3390/coatings14091227.
[21] F. Chen*et al.*, “Robust and durable liquid-repellent surfaces,” Chem. Soc. Rev., vol. 51, no. 20, pp. 8476–8583, 2022, doi: 10.1039/d0cs01033b.
[22] A. Sepehri, A. Kirichek, M. van den Heuvel, and M. van Koningsveld, “Smart, sustainable, and circular port maintenance: A comprehensive framework and multi-stakeholder approach,” *J. Environ. Manage.*, vol. 370, no. August, p. 122625, 2024, doi: 10.1016/j.jenvman.2024.122625.
[23] HG Lee, OH Yu, SL Kim, JH Kang, and KS Shin, “Species Composition and Distribution of Hull-Fouling Macroinvertebrates Different According to the Areas of Research Vessel Operation,” *J. Mar. Sci. Eng.*, vol. 12, no. 4, 2024, doi: 10.3390/jmse12040613.
[24] J. Hinrichs, “Biological recruitment on static and boat hull panels coated with non-toxic fiber flock,” *Plymouth Student Sci.*, vol. 15, no. 2, pp. 221–238, 2022.
[25] B. Hyun*et al.*, “Development of Biological Risk Assessment Protocols for Evaluating the Risks of In-Water Cleaning of Hull-Fouling Organisms,” J. Mar. Sci. Eng., vol. 12, no. 2, 2024, doi: 10.3390/jmse12020234.
[26] Y. Cho, SJ Kim, MS Kim, J. Yang, and J. Choi, "Development of efficacy capture test method for in-water cleaning system using artificial barnacles,"*Front. Mar. Sci.*, vol. 11, no. August, pp. 1–10, 2024, doi: 10.3389/fmars.2024.1404472.