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STUDY ON TECHNOLOGIES FOR PREVENTING AND REMOVING FOULING ON STEEL STRUCTURES IN COASTAL ENVIRONMENTS

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Abstract

In marine environments, particularly in estuarine regions of Vietnam, the adhesion of oysters and marine microorganisms to metal surfaces causes biocorrosion, significantly reducing the durability and operational efficiency of steel structures such as sluice gates. Although various technical solutions have been studied to mitigate this issue, a comprehensive approach that is both effective, environmentally friendly, and practical for field application remains elusive. Within the framework of a collaborative research project between Thuyloi University (Vietnam) and IHI Corporation (Japan), a combined technology using Micro-current and Ultrasonic irradiations was experimentally applied on a real sluice gate structure in Hai Phong. The results demonstrated that the solution effectively prevents and removes biofouling organisms, identifies optimal technical conditions for implementation in estuarine environments, and provides recommendations for selecting suitable gate materials to enhance corrosion resistance and extend structural lifespan.

Keywords: experimental technology; biofouling prevention; micro-current technology; ultrasonic irradiation; steel gate structures; corrosion resistance.

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1. General introduction

The rapid expansion of coastal and marine infrastructure has led to a significant increase in the use of steel structures in diverse applications, including tidal water regulation systems, seawater intrusion prevention sluices, shoreline protection works, renewable energy installations, and offshore oil and gas platforms. In particular, within the Agriculture and Rural Development sector, many steel regulating gates are constantly exposed to saline environments, making them highly vulnerable to biofouling [1, 2, 3]. One of the most common and problematic biofouling organisms in these environments is the barnacle—a sessile marine arthropod that firmly adheres to submerged surfaces by secreting strong adhesive substances. This adhesion can penetrate and damage protective coatings, thereby accelerating corrosion, compromising structural integrity, and reducing the visual and functional quality of the infrastructure. These issues become even more pressing in large-scale infrastructure projects that are increasingly integrated with tourism and environmental preservation initiatives.

Although corrosion protection methods, such as, the use of durable materials, anti-corrosion coatings, and sacrificial anodes have been widely adopted, biofouling prevention on submerged steel structures remains an under-addressed challenge. Critical structures affected include hydraulic sluice gates, offshore wind turbine foundations, steel pipe piles, steel sheet piles, subsea pipelines, and

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drilling rigs (Fig. 1). While conventional coatings provide a cost-effective and easily applicable solution, their service life is generally limited to only 1 to 5 years [4, 5, 6], necessitating the development of more sustainable, long-term alternatives

Figure 1. Biofouling on the sluice gates of the Cai Be project (two gates, 35 × 7.5 m)

Among emerging solutions, micro-current and ultrasonic irradiation technologies have shown considerable promise [7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24]. Unlike traditional physical or chemical removal methods, these approaches offer environmentally friendly, non-invasive means of preventing and detaching biofouling organisms with minimal operational disruption. Micro-current and Ultrasonic irradiation technologies present environmentally sound alternatives for preventing and removing biofouling with minimal disruption to operational processes. These technologies have been successfully implemented and patented in Japan [25, 26], warranting further investigation and adaptation to the specific conditions of Vietnam. Field surveys identified four sluices on the Hai Phong sea dike significantly affected by biofouling: Co Tieu 2, Co Tieu 3, C2, and Cam Cap. The C2 sluice was selected as the most suitable site for testing these technologies under Vietnam's conditions. This research, conducted through a collaborative effort between Thuyloi University (Vietnam) and IHI Corporation (Japan) [27], is currently being tested at the C2 culvert in Hai Phong city [28, 29], yielding initial positive results [30]. This paper summarizes the technological solutions and preliminary findings of this ongoing testing process.

2. Technology for preventing and removing fouling on steel structure surfaces

2.1. Micro-current technology

The underlying principle of the micro-current technology (Fig. 2) involves utilizing electrodes to induce an electrolytic reaction on the steel surface. This reaction generates a low-oxygen layer, which acts as a deterrent to the settlement of barnacle larvae in the aquatic environment [25, 26].

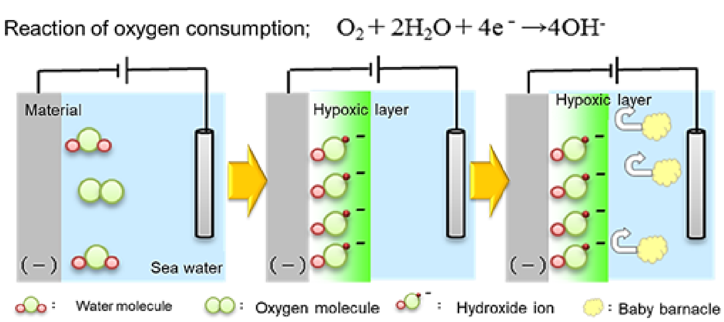


Figure 2. Principle of Micro current method for preventing surface fouling

2.2. Technology using ultrasonic irradiations

The ultrasonic generator operates by emitting high-frequency ultrasonic waves into the surrounding water. These irradiations create rapid fluctuations in pressure, resulting in the formation and collapse of numerous microscopic cavitation bubbles [25, 26]. The implosion of these cavitations generates localized forces that effectively penetrate and disrupt fouling organisms attached to the steel surface, thus achieving cleaning (Fig. 3).

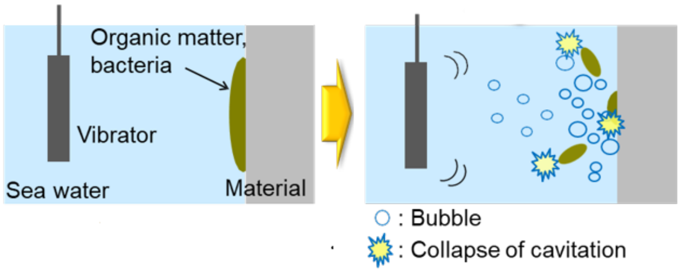


Figure 3. Principle of the ultrasonic method for cleaning surface fouling

3. Equipment installation

3.1. Experimental specifications

To ensure a robust assessment of the environmental impact on system performance, the experimental parameters in Vietnam's marine environment were carefully maintained, mirroring the baseline conditions established in prior studies conducted in Japan. The specific parameters for each technology are detailed below:

- Micro current method: Current density: -0.3 A/m^2; Distance between the test piece and the counter electrode: 300 mm.

- Ultrasonic method: Frequency of ultrasonic irradiations: 28 kHz; Output: 600 W; Distance between the test piece and the transducer: 268±5 mm.

3.2. Experimental procedure

The research team selected a site on the sea dike in Hai Phong city for the technology testing based on several key criteria: the frequent operation of steel gate valves in a seawater environment with existing biofouling; sufficient water depth to ensure continuous submersion of test samples; adequate space for equipment installation without significantly affecting the project's regular operations; accessibility to a power grid; and ease of protection and monitoring throughout the testing period. The equipment installation was conducted in two phases.

The initial phase, on March 19, 2024, involved the installation of equipment for the micro-current technology on the upstream wing wall, connected to a control system. Located on the working platform, four frames were deployed, each holding three steel test plates. These frames were designed to be easily raised and lowered for observation and photography, as well as to mitigate the influence of water flow during valve gate operation. For the micro-current testing, Frames (1) and (2) each contained three SS400 steel samples, while Frames (3) and (4) each contained three SUS323L steel samples. Each frame included two test plates connected to the micro-current and one unprotected control sample (Fig. 4).

The second phase involved the deployment and monitoring of samples for the ultrasonic irradiation technology, commencing on August 28, 2024. The ultrasonic transducer was positioned on the sluice gate side, adjacent to the micro-current test frames (Frame 5 in Fig. 4). Frame No. 5 housed six

100 × 150 mm steel samples, comprising two SUS323L, two painted SS400, and two SS400 coated with inorganic zinc-rich paint. The ultrasonic transmitter was placed opposite the lower row of these samples (Fig. 6).

For micro-current testing, install four frames. Frames (1) and (2) each contain three SS400 samples, while Frames (3) and (4) each contain three SUS323L samples. Each frame includes two protected samples and one unprotected control (Fig. 5).

For ultrasonic testing, install Frame No. 5 with six 100 × 150 mm steel samples (2 SUS323L, 2 Painted steel, 2 Inorganic zincrich paint steel). Position the ultrasonic transmitter opposite the lower sample row (see detail in Fig. 6).

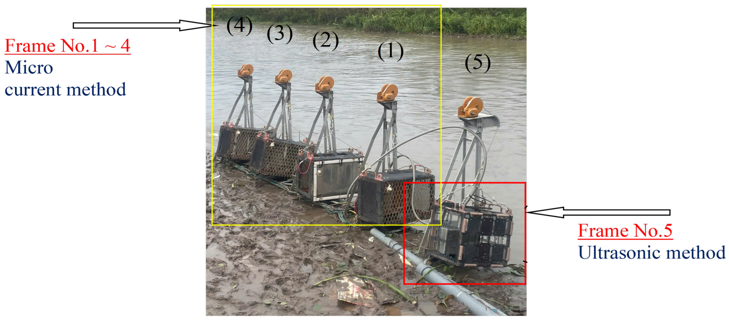


Figure 4. Frame position of the micro current method and the ultrasonic irradiation method

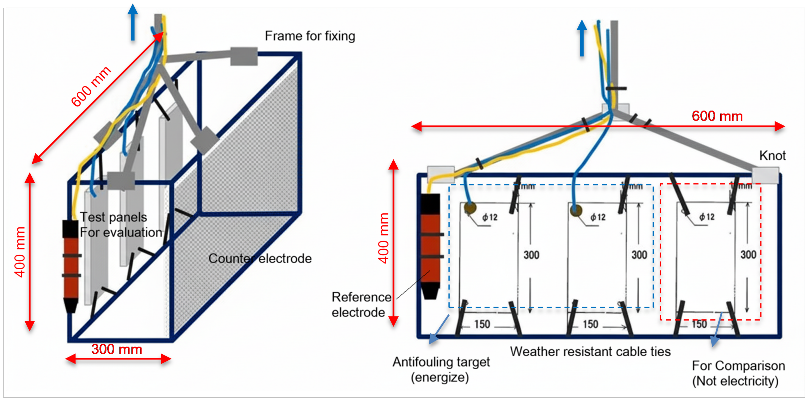


Figure 5. A fixed frame, test panels of the low current method

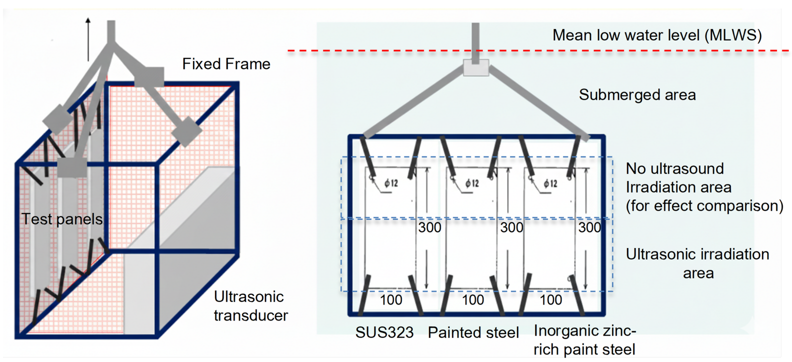


Figure 6. A fixed frame, test panels and a transducer of the ultrasonic irradiation method

All the frames were positioned at a depth of 0.5h, where h represents the maximum tidal water depth at the experimental site. This placement ensured a clearance of 0.5 meters from the seabed and prevented the panels from being exposed during the lowest tide level.

A summary of the materials used in the test is listed in Table 1, in which: Frames 1 to 4 represent tests conducted using the micro-current method. When micro-current was applied, no significant difference in antifouling performance was observed between SS400 and SUS323L. In contrast, under conditions without micro-current application, SS400 exhibited significant biological fouling, rust formation, and surface corrosion, eventually leading to material degradation. SUS323L, while demonstrating less corrosion compared to SS400, exhibited a similar level of biological fouling, which subsequently promoted crevice corrosion. Others, Frame 5 represents the test using the ultrasonic method, with test panels composed of three types of materials: SUS323L, SS400 coated with antifouling paint (film thickness: 305 µm) and SS400 coated with thick inorganic zinc-rich paint (film thickness: 75 µm). The results revealed, consistent with the pre-verification tests conducted in Japan, a notable difference in the prevention of organism attachment between conditions with and without ultrasonic irradiation. For SS400 coated with the thick inorganic zinc-rich paint, no significant difference was observed between irradiated and non-irradiated conditions. This outcome is likely attributed to the elution of zinc, a component known to repel marine organisms, which occurs regardless of ultrasonic irradiation.

Table 1. Material list for test

List	Process	Note of test panels
Micro Current Method		
Frame 1	SS400 carbon steel (1)	3 test plates (150 × 300) – No paint
Frame 2	SS400 carbon steel (2)	3 test plates (150 × 300) – No paint
Frame 3	SUS323L (underwater)	3 test plates (150 × 300) – No paint
Frame 4	SUS323L (tidal zone)	3 test plates (150 × 300) – No paint
Ultrasonic Irradiation Method		
Frame 5	SUS323L steel	2 test plates (150 × 100) – No paint
	SS400 (3)	2 test plates (150 × 100) – Paint
	SS400 (4)	2 test plates (150 × 100) – Paint

Note: (1) Steel is made by Japanese; (2) Steel is made by Chinese; (3) Steel (1) is coated with antifouling paint (film thickness: 305 µm); (4) Steel (1) is coated with thick inorganic zinc-rich paint (film thickness: 75 µm).

4. Effectiveness verification results

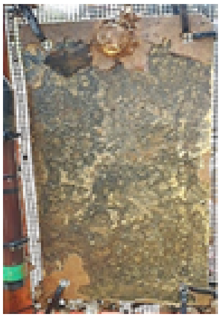
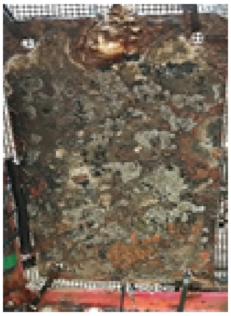
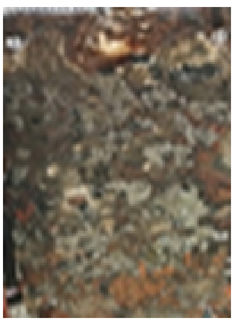
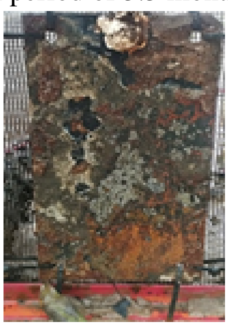
The effectiveness verification of the Micro current and Ultrasonic Irradiation methods was conducted with snapshot durations of 15 minutes per session, at a frequency of four times per day (totaling 60 minutes per day) at the following times: 1 st: 16:00–16:15/ 2 nd: 22:00–22:15/ 3 rd: 4:00–4:15/ 4 th: 10:00–10:15.

After nearly one year of applying this technology under the specific coastal conditions of Vietnam, initial positive results have been observed. The findings from both the micro-current and ultrasonic irradiation methods were compared to pre-verification studies carried out at Aioi Works in Japan [25].

4.1. Rules of microbial distribution

The application of micro-current demonstrated a sustained antifouling effect after 3.5 months (July 2024) and 9 months (December 2024). Table 2 illustrates the observed differences in microbial distribution over this period.

Table 2. In comparison, the antifouling effect after 3.5 months (July 2024) and 9 months (December 2024) [28, 30]

List	Connected to the low current		Non-Electricity
Frame (1)			
		A period of 3.5 months	
			
		A period of 9 months	
Frame (2)			
		A period of 3.5 months	
			
		A period of 9 months	

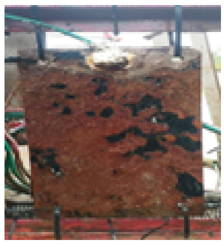
List	Connected to the low current		Non-Electricity
Frame (3)			
	A period of 3.5 months		
			
	A period of 9 months		
Frame (4)			
	A period of 3.5 months		
			
	A period of 9 months		

Observations from the control test panel (Frame 4) without any preventive measures indicated a significantly higher biofouling density during the summer months, with a reduction in fouling tendency during the colder season.

4.2. Results of Micro-current method

The 9-month pre-verification results demonstrated a clear difference in anti-biofouling effectiveness between test panels with and without the application of low current. Consistent with pre-verification studies in Aioi, Japan, the observed differences validated the efficacy of the micro-current method for biofouling prevention under the environmental conditions in Vietnam. The application of a micro-current resulted in the formation and subsequent peeling of an electrodeposition coating. Table 3 provides visual documentation of the maintained antifouling effect after 9 months of micro-current application.

Table 3. The antifouling effect was maintained even after 9 months when a micro current was applied (Photo date and time: December 10, 2024) [28, 30]

List	Overall fixed appearance	Connected to the low current		Non - electricity
		Panoramic photo of test piece 1	Panoramic photo of test piece 2	Panoramic photo of test piece 3
Frame (1)				
Frame (2)				
Frame (3)				
Frame (4)				

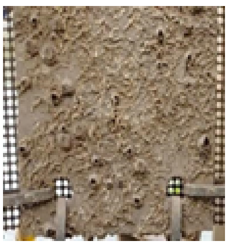
The data from Frames 1 to 4, representing the micro-current method tests, indicated no significant difference in antifouling performance between SS400 and SUS323L when micro-current was applied. Each frame includes two protected samples and one unprotected control. Conversely, in the absence of micro-current application, SS400 exhibited substantial biological fouling, rust formation, and surface corrosion, leading to material degradation. While SUS323L showed less corrosion than SS400, it experienced a comparable level of biological fouling, which subsequently contributed to crevice corrosion. SUS323L exhibits superior resistance to biofouling compared to SS400 steel due to its smoother surface finish. Additionally, its chromium-rich composition forms a stable passive oxide layer on the surface, which acts as an effective barrier against the adhesion and proliferation of marine organisms.

4.3. Results of ultrasonic irradiation method

The 6-month pre-verification results showed a distinct difference in anti-biofouling effectiveness between test panels subjected to ultrasonic irradiation (on Bottom) and those without (on Top). Plates on the left using SS400 coated with antifouling paint (film thickness: 305 µm) and plates in the center using SS400 coated with thick inorganic zinc-rich paint (film thickness: 75 µm). Other plates on the right are selected by SUS323L steel.

This outcome verified the effectiveness of the ultrasound method in preventing biofouling. Table 4 visually presents the maintained antifouling effect after 6 months of ultrasonic irradiation. This trend aligns with previous research (Fig. 7) conducted in Japan [24, 25].

Table 4. The antifouling effect was maintained even after 6 months when an ultrasonic irradiation was applied (Photo date and time: February 25, 2025) [28, 30]

Position	Close-up photo of test piece of left	Close-up photo of test piece of center	Close-up photo of test piece of right
Top			
Bottom			

For short-term applications (approximately six months to one year), the application of a thick inorganic zinc-rich paint (75 µm) appeared to offer a certain level of anti-fouling protection, likely due to the leaching of zinc. However, the elution of zinc leads to a reduction in the paint film thickness, significantly diminishing the corrosion resistance of the underlying material. Furthermore, the zinc itself corrodes in the marine environment, forming zinc corrosion products that reduce the anti-fouling effect over time. The research suggests SUS323L steel as a promising alternative material, which has been increasingly used in sluice gates in Japan and holds potential for future applications in Southeast Asia.

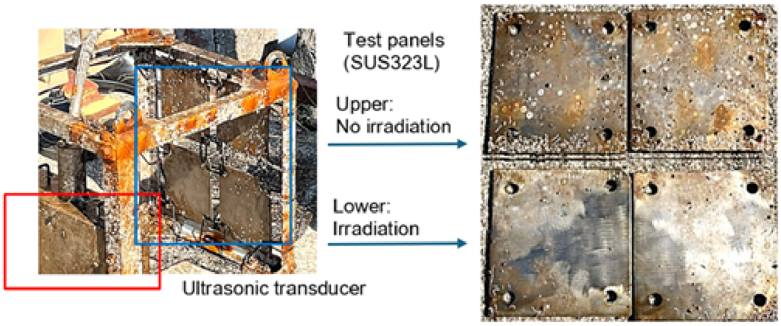


Figure 7. The Pre-verification of the ultrasonic irradiation method was conducted in Japan under the following conditions for about one and a half months from the beginning of September, when biofouling was noticeable

5. Conclusions and research plans

The initial testing of micro-current and ultrasonic irradiation technologies for preventing and removing fouling on steel structures in coastal areas has yielded promising results. However, it is crucial to acknowledge that these findings are based on visual assessments conducted during the early stages of testing. Therefore, further research involving real large-scale sluice gates is warranted to comprehensively evaluate the long-term efficacy and scalability of these technologies.

The research conducted during the testing process can be summarized as follows:

(1) The environmental conditions at the test site did not negatively impact the anti-biofouling capabilities of either technology. Both the micro-current and ultrasonic irradiation methods were implemented under conditions consistent with pre-verification tests conducted in Japan.

(2) Equipment should be placed in shallower water, where light penetration and marine life growth are greater. The anti-biofouling system is most effective from early May to late October when water temperatures are higher, promoting marine life proliferation.

(3) SUS323L steel is recommended for consideration in future tidal sluice gate projects in Vietnam and is anticipated to become a prevalent material choice in Asia, as it is currently utilized in sluice gate systems in Japan.

The two tested technologies exhibit significant potential for preventing biofouling while maintaining environmental safety, addressing the growing demand from water infrastructure operators for advanced anti-fouling solutions for large sluice gates. However, for practical implementation, further research, optimization of operational parameters, and the establishment of unit pricing, cost norms, and standardized maintenance procedures are necessary. Close collaboration with IHI Corporation is expected to facilitate the accelerated adoption of this technology in Vietnam.

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References

[1] Bishop, M. J., Mayer-Pinto, M., Airoldi, L., Firth, L. B., Morris, R. L., Loke, L. H., Hawkins, S. J., Naylor, L. A., Coleman, R. A., Chee, S. Y., Dafforn, K. A. (2017). Effects of ocean sprawl on ecological connectivity: impacts and solutions. *Journal of Experimental Marine Biology and Ecology*, 492:7–30.

[2] Dafforn, K. A., Lewis, J. A., Johnston, E. L. (2011). Antifouling strategies: History and regulation, ecological impacts and mitigation. *Marine Pollution Bulletin*, 62(3):453–465.

[3] Nguyen, N. H., Dong, V. K., Le, H. Q., Nguyen, V. C., Mai, V. M., Nong, Q. Q. (2025). Preliminary application results of an antifouling device in a tropical marine environment. *Journal of Tropical Science and Engineering (JTSE)*, 21:107–113. (in Vietnamese).

[4] Sousa-Cardoso, F., Teixeira-Santos, R., Mergulhão, F. J. M. (2022). Antifouling performance of carbon-based coatings for marine applications: A systematic review. *Antibiotics*, 11(8):1102.

[5] Li, L., Hong, H., Cao, J., Yang, Y. (2023). Progress in marine antifouling coatings: Current status and prospects. *Coatings*, 13(11):1893.

[6] Nurioglu, A. G., Esteves, A. C. C., de With, G. (2015). Non-toxic, non-biocide-release antifouling coatings based on molecular structure design for marine applications. *Journal of Materials Chemistry B*, 3 (40):6547–6570.

[7] Nakamura, S., Murayama, C. (1996). Anti-marine-biofouling by seawater electrolysis. *Bulletin of the Society of Sea Water Science, Japan*, 50(5):305–311.

[8] Chen, J., Li, Y., Anderson, A., Liu, S., Dai, L., Wang, L., Galang, M. G. K., Wang, Y., Liu, J., Zhou, N., Chen, Y., Lin, X., Cobb, K., Ruan, R. (2025). Evaluation and prevention of biofilm formation on stainless steel sensor mesh for effective biofouling mitigation. *Algae and Environment*, 1(1):4.

[9] Cao, S., Wang, J., Chen, H., Chen, D. (2010). Progress of marine biofouling and antifouling technologies. *Chinese Science Bulletin*, 56(7):598–612.

[10] Zhang, H., Ding, Q., Zhang, Y., Lu, G., Liu, Y., Tong, Y. (2024). Prevention and control of biofouling coatings in Limnoperna fortunei: A review of research progress and strategies. *Polymers*, 16(21):3070.

[11] Chang, Y. S., Munro, C. J., Fortunato, L., AlAli, A., Marciulescu, C., Harvey, S. L., Vrouwenvelder, J., Arafat, H., Dumée, L. F. (2024). Macrofouling remediation strategies for water intakes of desalination and other industrial plants – A review. *Desalination*, 590:117987.

[12] Obayomi, K. S., Mustapha, L. S., Yahya, M. D., Obayomi, O. V. (2025). Antimicrobial materials for water infrastructure: Mitigating biofouling and pathogen contamination. *Journal of Hazardous Materials Advances*, 20:100896.

[13] Qiu, Q., Gu, Y., Ren, Y., Ding, H., Hu, C., Wu, D., Mou, J., Wu, Z., Dai, D. (2024). Research progress on eco-friendly natural antifouling agents and their antifouling mechanisms. *Chemical Engineering Journal*, 495:153638.

[14] Liang, H., Shi, X., Li, Y. (2024). Technologies in Marine Antifouling and Anti-Corrosion Coatings: A Comprehensive Review. *Coatings*, 14(12):1487.

[15] Pourhashem, S., Seif, A., Saba, F., Nezhad, E. G., Ji, X., Zhou, Z., Zhai, X., Mirzaee, M., Duan, J., Rashidi, A., Hou, B. (2022). Antifouling nanocomposite polymer coatings for marine applications: A review on experiments, mechanisms, and theoretical studies. *Journal of Materials Science & Technology*, 118(19):73–113.

[16] Callow, J. A., Callow, M. E. (2011). Trends in the development of environmentally friendly fouling-resistant marine coatings. *Nature Communications*, 2(1):244.

[17] Liu, D., Shu, H., Zhou, J., Bai, X., Cao, P. (2023). Research progress on new environmentally friendly antifouling coatings in marine settings: A review. *Biomimetics*, 8(2):200.

[18] de Lannoy, C.-F., Jassby, D., Gloe, K., Gordon, A. D., Wiesner, M. R. (2013). Aquatic biofouling prevention by electrically charged nanocomposite polymer thin film membranes. *Environmental Science & Technology*, 47(6):2760–2768.

[19] Debiemme-Chouvy, C., Cachet, H. (2018). Electrochemical (pre)treatments to prevent biofouling. *Current Opinion in Electrochemistry*, 11:48–54.

[20] Long, Y., Yu, Y., Yin, X., Li, J., Carlos, C., Du, X., Jiang, Y., Wang, X. (2018). Effective anti-biofouling enabled by surface electric disturbance from water wave-driven nanogenerator. *Nano Energy*, 57:558–565.

[21] Jiang, H., Wang, Y., Du, F., Stolte, S., Specht, U., Pesch, G. R., Baune, M. (2024). A universal AC electrokinetics-based strategy toward surface antifouling of underwater optics. *Scientific Reports*, 14(1): 16125.

[22] Tang, Z., Zu, P., Chen, B., Zhang, X., Lan, J., Zhang, J., Zhang, H., Wang, B., Ma, L., Wu, J. (2025). Ultrasonic-assisted marine antifouling strategy on gel-like epoxy primer. *Molecules*, 29(19):4735.

[23] Huang, X., Niu, G., Xie, Y., Chen, X., Hu, H., Pan, G. (2024). Application of ultrasonic cavitation in ship and marine engineering. *Journal of Marine Science and Application*, 23(1):23–38.

[24] Salimi, M., Livadas, M., Teyeb, A., El Masri, E., Gan, T.-H. (2023). Biofouling removal using a novel electronic system for driving an array of high-power marinised transducers. *Applied Sciences*, 13(6): 3749.

[25] Fukase, K., Ito, Y. (2015). Development of materials with resistance to biofouling for sluice gates and underwater structures. *Journal of Marine Engineering*, 22(4):105–116. Proceedings of Annual Meeting of the Japanese Society of Fisheries Engineering.

[26] IHI Corporation (2016). Study of anti-biofouling technology for gate facilities. *IHI Engineering Review*, 49(1):46–50.

[27] IHI – TLU team (2024). *Joint Research Agreement Between Institute of Civil Engineering - Thuyloi University and IHI Corporation*.

[28] DaDo Exploiting Irrigation One Member Company Limited (2024). *Sample monitoring results report*.

[29] IHI – TLU team (2024). Preliminary research results on the trial application of anti-fouling technology for coastal steel structures. In *Thuyloi University's Annual Scientific Conference*, 220–223. (in Vietnamese).

[30] Institute of Civil Engineering (2025). *Research report on experimental surface cleaning methods against marine biofouling on sluice gates*.