PRELIMINARY ANALYSIS OF BIOFOULING GROWTH PROFILE- A FIELD STUDY OF OCEAN THERMAL ENERGY CONVERSION FACILITY

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ABSTRACT: Ocean Thermal Energy Conversion (OTEC) is a renewable energy technology that exploits temperature differences between warm surface ocean waters and cold deep ocean water to generate energy based on the principle of thermodynamic heat engine systems. Due to the system's direct contact with seawater, it has a high potential for becoming potential sites of unwanted accumulation and growth of biofouling such as microorganisms, plants, algae, or turnips on wet surfaces. Based on the future location of OTEC facility in Port Dickson, Malaysia, no specific study has been done to evaluate potential biofouling, particularly its minimum period for growth stages in this site. Therefore, this study focuses on conducting preliminary assessments of biofouling growth profile on the coastal area where OTEC facility could be deployed. These proposed research activities involved direct field work where two cages containing a set of coupons for biofouling growing sites were immersed in the coastal area in Port Dickson beach. The collected samples were collected periodically within six weeks and analyzed accumulated weight of sample and area covered by visible macrofouling on the immersed coupons. The results biofouling formation particularly visible macrofouling samples could occur after a minimum of three weeks. It was proven with clear and visible presence of macrofouling samples, likely to be *perna viridas* (green mussels) and *balanus glandula* (acorne barnacles). In addition, a drastic increase in the accumulated weight of sample was recorded between 21st day to 41st day (during the fourth visit) for almost 25$^{\%}$ and the covered area was recorded for more than 50%. Although there is no clear quantitative and consistent data of biofouling growth profile from the accumulated and covered area sample, this preliminary assessment provides a good basis for the next biofouling study as it provides input for the minimum period for biofouling assessment.

KEY WORDS: *Ocean thermal energy conversion (OTEC), biofouling*

1. INTRODUCTION

OTEC is a promising renewable energy technology that capitalizes on the temperature difference between warm surface waters and cold deep-sea waters to generate power [1]. Based on its thermodynamic operation, the OTEC works like a heat engine system that offers convenient, yet reliable energy sources particularly in remote locations in tropical regions. In the context of Malaysian coastal area which has warm tropical climate and proximity of shoreline close to deep sea water area, there is huge potential of OTEC implementation in this country, particularly in east coast area in Sabah [1]. Due to high demand for fossil-free energy resources and the significant concern of reducing greenhouse effects, OTEC has a huge potential contribution to renewable energy portfolios, providing both electricity generation and auxiliary benefits such as seawater desalination and other potential side activities for economics such as aquaculture cultivation and rare mineral extraction industries [2].

As the system has direct physical contact with seawater, there is inevitable consequence on the potential growth and settlement of microorganisms, algae, and other organisms on any physical surface which are in contact with seawater. Biofouling is the result of undesired deposition of all forms of biological elements on immersed materials [3]. Biofouling poses a major problem of marine-based systems, like ships, aquaculture, and energy facilities including OTEC, potentially degrading system efficiency and creating operational problems. In the case of OTEC facilities, the accumulated biofouling on equipment such as heat exchangers and pipelines may hamper the process of heat transfer and increase energy consumption with rising maintenance costs [3]. For example, the presence of a thin biofilm of 25-50 micrometers could reduce the performance of OTEC by 50% [1]. Biofouling can also lead to full collapse in extreme cases, in this example, large macrofouling that is swept away by strong flow in pipeline may cause serious damage to the downstream processing facilities [1].

Biofouling occurs when diverse biological life forms undesirably build up on submerged materials, originating with microbial adherence leading to the development of biofilm and followed by the colonization of macrofouling organisms. This process eventually contributes to the accumulation of mature biofoulants that can detach from surfaces and disturb aquatic ecosystems[4]. The prolonged colonization process allows the attachment and growth of invertebrate larvae and the spores of algae on the submerged surface [4]. Among these macro biofouling species are such as barnacles, mussels, sponges, sea anemones and hydroids, bryozoans, serpulids, algae and others [5]. However, it should be noted that factors such physicochemical properties of water, biological factors, geographical factors as well as physical setup of substrate, may indirectly affect different degree of biofouling growth profile and species [5]. Figure 1 illustrates schematic stages involved in biofouling growth and deposition on the exposed surface.

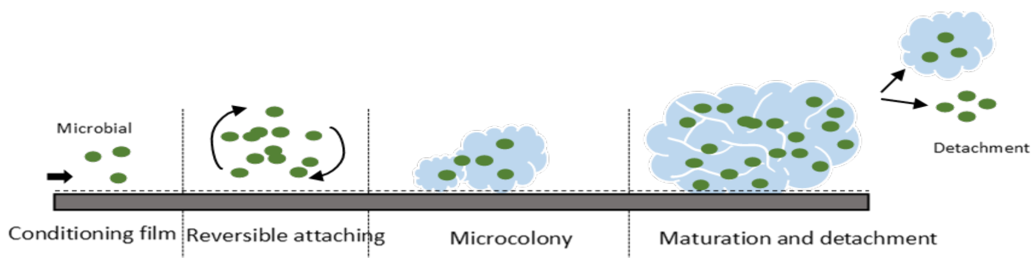

Fig. 1. Stages involve in biofouling growth and deposition on an exposed surface [5]

In the proposed experiment, the coastal area near Port Dickson, Negeri Sembilan is selected as the biofouling field location where a proposed hybrid OTEC laboratory facility which was recently completed in early 2024 is located at this coastal area. Based on previous observation conducted, the main focus for the biofouling setup would be on the surface water intake point which is prone to severe blockage due to biofouling built up on the surface.

Considering that biofouling is an inevitable and exclusive problem with reference to the sample of seawater itself and other factors, it is crucial to represent such setup in realistic, yet practical settings. There are several approaches which could be considered: a field study approach where potential biofouling growth naturally by immersing a substrate (an exposed, physical surface) into open seawater environment [4], a biofouling monitoring chamber that connects incoming stream of water and allows accumulated biofouling to be monitored or a synthetic-based biofouling generative system which imitates the resemblance of biofouling growth and accumulation [6]. In this case, the field study approach is selected as it offers realistic biofouling growth and adhesion profile of concern surface.

Based on the recorded observation, as the threat of biofouling is certain, there is a need to analyze minimum period taken for biofouling growth, specifically visible macrofouling, on the concerned substrate. Until now, there is no scientific evaluation that has been made to assess biofouling particularly in this area concerned location. In this case, the information on the minimum period of macrofouling growth is crucial as it subsequently allows future biofouling evaluation and preventive activities could be conducted successfully. Therefore, these proposed research activities aim in conducting preliminary study of potential macrofouling growth profile, specifically at the potential site of OTEC facility.

The current study is on biofouling that takes place within a hybrid OTEC plant based in Port Dickson, Malaysia. The plant relies much on seawater regarding energy generation and desalination; it therefore provides one of the most ideal case scenarios for a field experiment of biofouling within an operational context. Biofouling sampling devices shall be put into place in determining the extent of biofouling on High-Density Polyethylene Pipe (HDPE) surfaces over a fixed period. Weight and dimensional changes in the materials over time will be measured to provide further detail about the growth profile of biofouling and possible variables in its severity [7].

2. METHODOLOGY

2.1 Cage Design

In this work, two submerged cages containing number of plates containing a set of coupons were formed by mounting two perforated, plastic-made trays together (Fig 2). The design intends to be a protector for the plastic boards that were placed inside this cage. Each cage contains four plastic boards that were with cable ties, where six high-density polyethylene pipes (HDPE) flat coupons, each with the square size of 2.5 cm x 2.5 cm were attached to a plastic board using Velcro strips (Fig 3). The usage of Velcro strips helps to attach the coupons to the plastic board and to re-attach them back when they were pull out for weight measurement purpose. The cages were later tied to a rope, length between 2-3 meters, where the rope was tied to heavy rocks that acts as an anchor. The long rope indirectly helps to re-adjust the depth of immersed cage in the case where there is fluctuation of seawater depth due to changes in seawater tides. In addition, as an indicator or buoy to the cage, the cage was tied to simple buoy as an indicator.

Fig. 2. Design of a cage

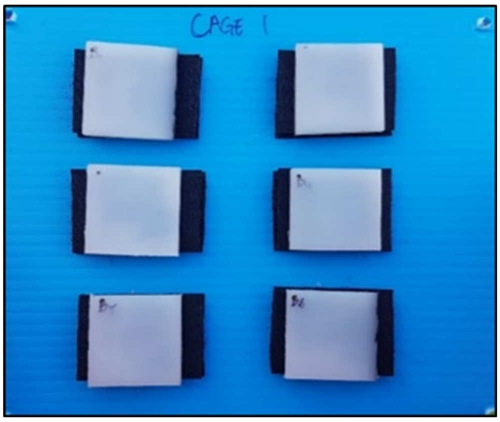

Fig. 3. Arrangement of coupons without any biofouling settlement

Unlike a typical directly exposed plates which were adopted in several research paper [8], the coupons were normally fixed on permanent structures that immersed inside the seawater such as poles, concrete structures or on heavy, submerged structure. However, due to strict requirements and safety reasons, the current immersed cage design is adopted. In this work, it was assumed that there is no significant variation of expected biofouling growth profile between closed and direct exposed system where the variation might be due to restricted seawater velocity. The cage was submerged with 1-2 feet above the sea floor to ensure they were minimum silt deposition on the cages while maintaining the cage immersed in seawater.

2.2 Location of Biofouling Sampling Site

Figure 4 shows the biofouling sampling site for this study which is located at the same location as the Ocean Thermal Energy Conversion (OTEC) facility in Teluk Kemang, Port Dickson. This location was carefully chosen for its suitability in maintaining consistent seawater properties, which are crucial for the accuracy of the study. Factors such as pH levels, salinity, and temperature were considered to ensure that the seawater environment remains uniform throughout the duration of the sampling. Based on previous study conducted earlier and on-site measurement, temperature of seawater was recorded within 28°C -30°C. The pH level of fresh collected seawater was recorded between pH 7.5-8, which is typical pH level for seawater [9] and salinity level was recorded between 24 parts per thousand (ppt), where it is slightly lower than average salinity level of 35 ppt [9]. Note that the measurement of temperature, pH level and salinity was done within the same vicinity of coastal area at different periods of assessment where it is assumed that this data is almost consistent with slight deviation. By selecting this site, it will minimize the risk of variation in the collected data, allowing for more reliable and comparable results across different sampling periods.

Fig. 4. Location of each cage

The two proposed cages were submerged in the seawater at a specific area located behind the I-Aquas facility. The exact coordinates of the cages are 2.46°N latitude and 101.84°E longitude. Both cages were located roughly 20-30 meters apart from where the placement is for acquiring variation in collected samples. The estimated surface water intake of OTEC is approximately 100-150 meters from the shoreline and considered to be shallow water depth (estimated depth to be 6-8 meters). Therefore, this selected location is adequate to optimize the exposure of the cages to natural marine conditions while ensuring that the physical properties of the seawater are as close as possible to those encountered at the OTEC facility.

2.3 Period of Assessment

The period of assessment for this work was conducted for less than two months (about 6 weeks). In the literature sources, there is no specific time required for the placement of biofouling in an open field site, where it could be within 30 days up to almost two years of assessment [10]. However, as this assessment intends to detect any visible appearance of potential biofouling, then the analysis was conducted for a minimum of two months. Over time, biofouling accumulation at the water intake has been noted to reach critical level of severity after approximately three weeks where visible macrofoulant could be observed. This period allows for significant biofouling development, including the growth of various marine organisms such as tunicate and barnacles, which tend to colonize submerged surfaces.

Throughout this period, the cages are monitored on a per-visit basis. This frequent observation schedule is critical to accurately track the time taken for biofouling to form, as well as the rate at which it progresses. Per-visit inspections allow for the capture of detailed data regarding the early stages of biofouling, which can be crucial in understanding the timeline of organism attachment and growth. It also provides the opportunity to record any changes in biofouling intensity, which could be influenced by short-term environmental changes such as shifts in water temperature or seasonal events.

2.4 Method of Assessment

This section will explain the method that was selected for analyzing the sample of biofouling. It will cover weight measurement and area covered assessment.

2.4.1 Weight Measurement

One of the key methods employed for assessing biofouling formation in this study is through weight measurement, a widely used technique that provides a quantifiable indication of the accumulation of biofouling on surfaces. Each of the coupons was weighed before it was attached to the Velcro. The initial weight for each coupon was recorded to obtain the difference in weight for each of the coupons. The coupons that show the formation of macrofouling for each visit will be collected and allowed to dry before being weighed. The difference in weight of the coupon will be recorded to know the severity of the biofouling formation for each cage. A total of 24 various coupons were analyzed in terms of weight.

2.4.2 Area Covered

Area covered are one of the assessment methods that was chosen to analyse sample of biofouling. In this work ImageJ software was used to analyse the area of coupons that was covered by the formation of biofouling providing quantitative data on the extent of macrofouling formation. In this study, eleven different coupons from out of total 36 coupons used were analyzed within period of 41 days.

3. RESULTS

Table 1 summarize the data collection of coupons over four visits done from June to July 2024. The first visit on 9th June 2024 marks the day the cages were submerged into the sea. The second visit happen 13 days after the first visit which is on 22nd June 2024 where 8 coupons were collected. There were also 8 coupons collected on third visit which occurs on 30th June 2024. On the last visit on 20th July 2024, 20 days after the previous visit, 14 coupons were collected which total to 30 coupons collected to be analysed during these 4 visits.

Table 1: Summary of coupons collection over four visits (June-July 2024)

Visit	Date	Day	No. of Coupons Collected
1^{st}	9^{th} June 2024	0	0
2^{nd}	22^{nd} June 2024	13	8
3^{rd}	30^{th} June 2024	21	8
4^{th}	20^{th} July 2024	41	14

3.1 Percentage of Weight Difference

The percentage weight difference of coupons during several visits for Cage 1 and Cage 2 were shown in Fig. 5 and Fig. 6, whereas Fig. 7 displays the average percentage weight differences for both cages throughout various visits. Biofouling development in Cage 1, which is indicated by weight differences, was minimal during all visits. Its average weight difference was 0.13%. 0.36% and 0.25% for the second, third and fourth visit, respectively, with individual coupons values varying from 0% to 0.43%.

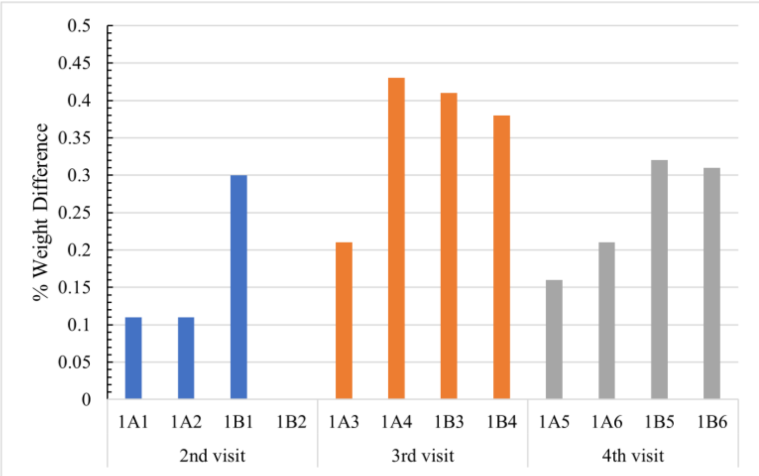

Fig. 5. Bar chart of percentage of weight differences vs the number of visits for Cage 1.

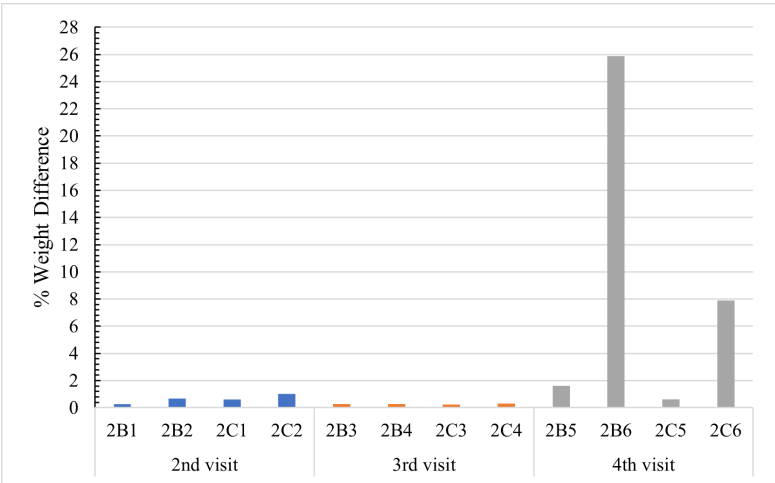

Fig. 6. Bar chart of percentage of weight differences vs the number of visits for Cage 2.

Conversely, Cage 2 showed more significant biofouling growth, especially during the fourth visit. The average percentage difference rose markedly from 0.65% on the second visit to 9.00% on the fourth visit. This significant rise was primarily driven by extreme outliers, like 25.87% for coupon 2B6 and 7.90% for coupon 2C6, On the third visit, Cage 2 exhibited more consistent biofouling, with an average of weigh difference of 0.27% and individual coupon measurements between 0.25% and 0.31%. The significant weight difference noted in Cage 2 on the fourth visit are likely caused by seasonal environmental changes such as rising seawater temperatures and increased nutrient levels, which have been known to accelerate biofouling growth [11].

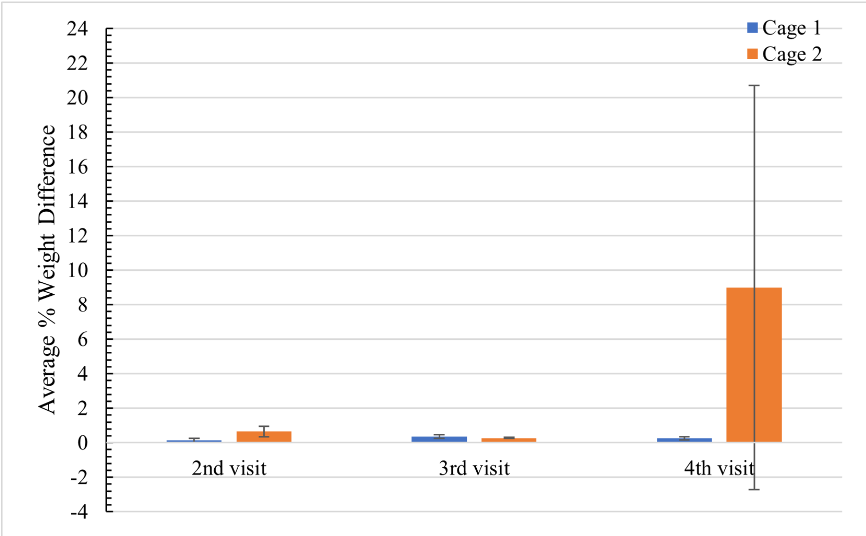

Fig. 7. Bar chart of average percentage of weight differences vs the number of visits for Cage 1 and 2.

3.2 Surface Area and Percentage of Coverage

Referring to Table 1, which displays data obtained from ImageJ software, revealing the surface area and percentage of biofouling coverage on various coupons on the third visit. The data shows biofouling coverage on the coupons was modest, ranging from 3.32 mm² to 8.31 mm², corresponding to coverage percentages of 0.53 to 1.28%. Table 2 shows biofouling had significantly increased, particularly on Plate A on the fourth visit. Coupon 2A3 had the highest fouling coverage at 438.81 mm² (67.51%). Furthermore, Plates B and C showed significant biofouling, with Coupon 2B6 covering 55.52% and Coupon 2C6 covering 20.57%. These results show a significant rise in biofouling growth between the third and fourth visits. Surface area measurements revealed that biofouling increases over time [11].

It is essential to acknowledge that for the second visit, there is no biofouling surface area and percentage of coverage data because of the absence of its parameter, which is macrofouling. Regardless of these limitations, a clear trend of increasing fouling coverage over time shown by the observed biofouling buildup between the third and fourth visits suggests significant fouling evident during the last visit.

Table 2: Surface area and percentage of biofouling coverage on various coupons on third visit.

Plate	Coupons	Area of Biofouling Coverage [mm^2]	Percentage of Biofouling Coverage [%]
B	1B4	3.32	0.53
C	2C4	8.31	1.28

3.3 Species

Fig. 8 depicts part of the biofouling that adheres to the HDPE pipe coupons. *Balanus Glandula* [12] and Grain mussel [13] were among those found biofouling. These macrofouling organisms contribute to the formation of dense biomass layers as they adhere to surfaces already colonized by microbial biofilms, which helps to explain the observed increases in weight and surface coverage.

Fig. 8. Biofouling adherence to the high-density polyethylene (HDPE) pipe coupons

4. DISCUSSION

The results presented earlier show that biofouling can rapidly build on submerged HDPE pipe coupons, especially as environmental conditions improve, such as a rise in seawater temperature and an increase in nutrient level. Initially, visible macrofouling occurred slowly, with average weight variations of 0.13% and 0.65% in the second visit and 0.36% and 0.27% in the third visit for Cage 1 and Cage 2. This suggests a relatively low variation of biofouling growth throughout these periods. However, during the fourth visit, there was a significant rise in biofouling, especially for Cage 2, with average weight increases of 9.0% meanwhile Cage 1 exhibits a value of 0.25%. The result of average percentage weight difference, particularly for Cage 2, shows that biofouling has an exponential development pattern, with a delayed development in the first three weeks, followed by fast accumulation in the last three weeks of assessment period [11].

The surface coverage analysis backs up this observation (Table 3), with minor fouling on the third visit and a significant rise by the fourth visit. Plate A was the most affected, specifically Coupon 2A3, which had 67.51% biofouling coverage on the fourth visit. This widespread fouling is relevant because it demonstrates the vulnerability of untreated materials in marine environments. Plates B and C, although less affected, exhibited significant biofouling, with coverage rates of 55.52% and 20.57%, respectively. These findings suggest that biofouling can spread rapidly in a short period of time, posing operational challenges to marine energy systems such as OTEC.

Table 3: Surface area and percentage of biofouling coverage on various coupons on fourth visit

Plate	Coupons	Area of Biofouling Coverage [mm^2]	Percentage of Biofouling Coverage [%]
A	2A1	27.76	4.63
	2A2	252.87	40.46
	2A3	438.81	67.51
	2A4	16.26	2.40
	2A5	13.31	2.05
	2A6	260.28	41.64
B	2B5	79.89	12.29
	2B6	360.88	55.52
C	2C6	133.70	20.57

Based on visual analysis, there were two possibility types of visible macro biofouling organisms that colonized the immersed coupons, which are *perna viridas* (green mussels) and *balanus glandula*. The physical characteristics of flat, shell-like appearance attached bio foulant resemble the early stage of the green mussels that could grow forms within a period of 3-4 weeks were shown in Fig. 9 [14]. On the other hand, the least form of biofouling observed is the acorn barnacles which have the shape of cone-like structures. The presence of these visible results shows that the presence of macrofouling could form within the period of 4-6 weeks.

In terms of experimental setup, as the cages were immersed in an open coastal area, they were subjected to changes of physico-chemical parameters, thus the results generated could not be possibly consistent and prone for various changes. This is expected as the potential biofouling may grow and attach to non-coupon sections of the setup such as the base plates. Therefore, for practical purposes, it is assumed that several parameters such as temperature, pH level, salinity and oxygen content are assumed to have insignificant change towards biofouling growth and attachment profile. In addition, the usage of closed cage setup, the arrangement of the plates and the effect of variation of flow profile were also omitted.

This study indicates the vital importance of effective biofouling prevention measures in maritime environments. The rapid biofouling found in this study, particularly within six weeks, emphasizes the significance of timely intervention. Anti-fouling coatings, regular cleaning techniques, and biological control should all be considered to reduce biofouling's impact on operating efficiency. Without such precautions, biofouling can quickly worsen, resulting in considerable performance losses and increasing operational expenses [15].

Fig.9. Early stage of the green mussels that could grow within a period of 3-4 weeks

5. CONCLUSIONS

Therefore, this work represents that biofouling, especially macrofouling, has immense possibilities to develop onto surfaces exposed to seawater within a remarkably short period of time. It becomes evident from the results that even after three weeks, there is a steep increase in biofouling, as evidenced by a sharp rise in weight and area coverage of the test coupons. In particular, the control plate had highly remarkable biofouling coverage. This indeed shows that materials exposed to marine environments are highly susceptible to fouling and may contribute to immense operational and maintenance costs for systems such as OTEC plants. The results, therefore, emphasize timely implementation of effective anti-fouling measures to avoid such biofouling growth, which tends to increase operational costs and reduce system efficiency when not dealt with appropriately. Moreover, it is suggested that though weight analysis provides very useful insights, complementary methodologies must be considered to capture a broader understanding of the dynamics of biofouling across different marine conditions.

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