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Bacteriological and Physicochemical Influences of Biofouling and Biocorrosion on Ship Hulls: Case Study of Ibaka Deep Sea Port

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Abstract

This study examines the bacteriological and physicochemical impacts of biofouling and biocorrosion on ship hulls at Ibaka Deep Sea Port. The study area, Ibaka Deep Sea Port, presents an exceptional coastal environment with abundance of microbial life and composite physicochemical dynamics, making it an ideal location for examining these interactions. Samples of biofilms were collected from stationary and mobile ship hulls, seawater and sediments using sterile procedures. Total Culturable Heterotrophic Bacteria (TCHB) count was used to enumerate and the bacterial isolates identification was through biochemical investigations. Results revealed lower counts on stationary ship hulls (1.34×10^7 cfu/g) and in seawater (7.07×10^6 cfu/g) with high bacteria counts on mobile ship hulls (5.66×10^8cfu/g) and sediments (7.78×10^8 cfu/g). The identified predominant bacterial isolates: Bacillus sp., Pseudomonas sp. and Corynebacterium sp., are notorious for their roles in biofouling and biocorrosion. Seawater, sediment and ship hull samples' physicochemical analysis indicated significant variances in parameters such as temperature, pH, chloride, organic carbon content and sulphate, which are key in influencing microbial colonization and metal corrosion. The seawater revealed conducive conditions for biofouling and biocorrosion, with high concentrations of chloride (12263 mg/kg) and a moderately alkaline pH (7.36), while the sediment presented higher acidic pH (5.7) and higher metals concentrations like copper and zinc. The study findings highlight the significance of understanding the interconnection of microbial communities and maritime settings environmental conditions. Effective management approaches, together with the utilization of antifouling coatings and consistent maintenance, are important to lessen the adverse influences of biofouling and biocorrosion on maritime substructure.

1.0. Introduction

The coastal environment, especially in deep-sea and maritime regions, offers a dynamic ecosystem interaction of various bacteriological communities with physicochemical parameters to form biogeochemical developments. Recently, the Onne-Port Harcourt deep seaport has attracted much attention, an area characterized by its exclusive ecological features and industrial consequence [1]. This coastal region is cited at the confluence of the Ibaka deep sea and the Ibeno Atlantic, harbors an overabundance of microbial life forms and involvements of complicated physicochemical dynamics, presenting an ideal situation for examining the interaction between microbiology and environmental chemistry disciple.

Recently, the Calabar deep seaport has attracted much attention, an area characterized by its exclusive ecological features and industrial significance. This coastal region, situated at the confluence of the Calabar River Estuary and the Cross River Estuary, as well as near the Ibaka deep seaport, harbors an overabundance of microbial life forms and involves multifaceted physicochemical dynamics, presenting an ideal situation for examining the interaction between microbiology and environmental chemistry disciplines. A water quality classification outline has been established for the Calabar River Estuary. The classification of water sources is made by reference to mathematically obtained Quality classification and Quality index tables. This source and models application have their significance [1].

The term used in nautical and industrial fields is known as fouling, subsequently approved by marine ecologists, to denote to oceanic ecosystems comprising of creatures attributed to (epibionts), bore into (infauna) or then animate on solid artificial or natural substrata [2]. According to [3] definition, biofouling as common structures immersed in marine location, as well as the nautical hulls such as dock ferries, which are for day-to-day commercial services. The presence of biofoulers have caused a lot of economic costs, such as mussels, algae and barnacles on the submerged vessel hulls of ships, since the weight or the organism's burrowing activity have the potential of causing structural damages, blockage intakes and plodding vessels, resulting in increase in dry-docking expenditure, amplify drag, higher fuel consumption.

Paramount, the two processes important in maritime industries are biofouling and biocorrosion, as they largely influence the microbial colonization and physicochemical properties of seawater and sea-bed sediment [4]. Biofouling is known as the undesirable microbial accumulation on surfaces submerged, and biocorrosion is the microbial-mediated materials deterioration, causing significant challenges to coastal infrastructure, resulting to environmental concerns and economic losses [5]. Knowing the fundamental mechanisms driving these developments in the Ibaka deep seaport is vital for effective implementation to mitigate strategies to preserve the maritime ecosystems [6].

Nautical vessel fouling is one of the major problems faced by shipping industries. Colonization of the ship or vessel metal parts by micro and macro-organisms such as bacteria, fungi dead animals and plants and result in the process known as biofouling [7].

Biofouling on ships causes vessel frames deterioration and increases the surface unevenness which, in turn, results to frictional resistance and speed depletion, causing high fuel consumption rate [8, 9]. In most marine vessels, the surface conditions of the hulls are primarily important in their performance. Frictional drag on some vessel-types can account for as much as 90% of the over-all drag even when free of fouling. For many years, and on this cause, frictional drag predictive understanding has been an inactive research area. Numerous studies have examined the surface roughness effects on the frictional drag of coated layers. Biofouling is a significant problem for heat exchangers and condensers in the cooling of industrial systems. It results to undesirable effects, such as loss of efficiency in heat exchanger, cooling circuit pipes blockage and adverse effects on plant performance in the course of time [10].

Investigations have been carried out in several studies on the microbial communities linked to biofouling and biocorrosion in nautical environments. [11] in 2016, provided insights into the surface colonization by microorganisms and the processes involved in the development of biofilm in maritime environments, stressing the roles of microbial adhesion, exopolymeric substances production, and biofilm formation quorum sensing. [4] in 2019, studied on the diversity and

abundance of archaea and bacteria in biofilms, highlighting the microbial interactions importance and community dynamics processes involved in bio-fouling.

Biofilm formation caused by bacterial and fungal on a variety of mineral substrates, illuminating the influencing factors responsible for biofilm development and microbial adhesion in maritime environments [5]. [6] in 2009, also deliberated on the impacts and mechanisms of corrosion influenced by microorganisms in numerous industrial settings, stressing on the essence of understanding microbial metabolism and processes involved in corrosion as well as control strategies.

The economic consequence of biofoulers slowing the speed of ship-hulls, can result to expensive dry-docking, slog, high fuel consumption and corrosion [2]. Inadequate information on safer biological procedures to lessen the challenges posed by bio-fouling and biocorrosion. The relationship between the underlying agents and maritime equipment corrosion. There is a rising concern for models' development to determine the fate of stationary and mobile maritime vessels.

This paper is aimed at providing a comprehensive examination of the bacterial agents and physicochemical composition of seawater responsible for biofouling and biocorrosion of ship-hulls plying the Ibaka Deep Sea. Through bacteriological and environmental chemistry integration approach of exploring the bacterial communities, diversity and composition to evaluate significant physicochemical parameters, and unveil the roles in the biofouling and biocorrosion dynamics [5, 11]. Furthermore, it will highlight the consequences of the research outcomes for maritime industries and the knowledge gaps as well as the scientific study of Ibaka deep seaport context.

2.0. Methodology

2.1. Study Area

Ibaka is a coastal community situated in the south-south region of Nigeria centered on Longitude 8.32^{o} and Latitude 4.65^{o}N E with land area of approximately 50 km^{2} and population 21,600 as estimated [12]. It is located along the maritime borders with Cameroon to the east, northern Cross River State, Gulf of Guinea (GoG) in the Southern end of Nigeria and Equatorial Guinea to the south [13]. It is Deep Sea terminal are critical to the economic landscape of Nigeria, with outstanding roles and attributes. It is in the progress phase as a deep-sea terminal, with focus on becoming a significant maritime trade hub, which requires environmental conservation efforts and substantial infrastructural investments. This area faces the unending challenge of harmonizing economic development with environmental sustainability and share a rich biodiversity.

2.2. Sample Collection

The collection of biofilms was done by scraping the ship hulls' surface using sterile scrapers, designed to lessen contamination and ensure representative collection of samples, and the biofilm samples were then transferred to sterile containers, and seawater was collected using sterile BOD bottles and sediments using Eckman grab samplers for examination [14]. Samples were obtained over a duration of two months, justifying a representative dataset for investigation; 30 biofilm samples in total were collected from ship hulls (15 from mobile ships 15 from stationary ships) using sterile scrapers designed to reduce contamination, with each sample transferred into sterilized containers for laboratory examination. Seawater samples were obtained from 10 dissimilar locations within the harbor area to ensure spatial variations, with the aid of a sterile BOD bottles at a steady depth of about 1 meter below the surface, resulting in a total of 20 seawater samples obtained over the duration of study. Sediment samples were obtained from 10 different sites within the seaport area using Eckman grab samplers, justifying the collection of surface sediments most probable to

interrelate with microbial communities, resulting in a total of 20 sediment samples obtained over the duration of study. The sampling sites for both sediment and seawater were strategically selected to encompass areas near stationary ships, areas regularly steered by mobile ships, and control locations away from direct activity of ships, with sampling conducted once monthly for two months, resulting to 70 samples in total (20 seawater, 30 biofilm, and 20 sediment), ensuring a wide-ranging dataset to examine the biocorrosion and biofouling impacts on ship hulls at Ibaka Deep Sea Port.

2.3. Bacteriological Analysis

2.3.1. Enumeration of Total Culturable Heterotrophic Bacteria (TCHB)

This analysis was carried out to determine the bacteriological sample titre. About 10 grams sample (sediment and ship hull scrap) while 10ml of seawater were dislodged into 90ml sterile normal saline. The analysis was adopted using spread plating method of nystatin fortified nutrient agar (62.5microgramme/100ml). With appropriate dilutions technique, 0.10ml aliquots were inoculated into sterile cool nutrient agar duplicated pour plates. Samples were obtained from both mobile and stationary ship hulls for microbial analysis. The inoculated plate was sealed and incubated to grow for 18-24hours at 37^0C. Titre was calculated in $cfug^{-1}$ using the formula below [15].

$$cfug^{-1} = \frac{No\ of\ colonies\ X\ dilution\ factor}{Amount\ used} \quad (1)$$

2.3.2. Physicochemical Analysis

Physicochemical parameters analysis of the water samples using standard methods employed are as described below:
The selected physicochemical properties of the freshwater determined throughout this study were temperature, pH, total dissolved solids (TDS), dissolved oxygen (DO), chemical oxygen demand, (COD), electric conductivity, salinity, nitrate, phosphate, copper, lead, zinc, chromium and cadmium. These properties are impact indicators in the environment for biocorrosion assessment [16, 17, 18].

4.0. Results and Discussion

Physicochemical and bacteriological characteristics of samples obtained for this study was analyzed and presented in Table 1.

Table 1: Total Culturable Bacterial Count (TCBC) of Maritime Samples

Samples	Bacterial count
Seawater	7.07×10^6 cfu/g
Mobile ship hull	5.66×10^8cfu/g
Stationary ship hull	1.34×10^7 cfu/g
Sediment	7.78×10^8 cfu/g

Mean Standard Error, using Least Significant Difference (LSD); p-value < 0.05. The alphabets and asterix was used to indicate the points of relatedness of the data tested. The points with same or alphabets suggest both data is related. The difference in the data suggest points of statistical significance.

The data presented in Table 1 indicates the Total Culturable Bacterial Count (TCBC) for the maritime samples in this study and expressed in colony-forming units per gram (cfu/g). The samples include seawater, mobile ship hulls, stationary ship hulls, and sediment. The ranges of bacteria count for each sample as statistically analyzed using the Least Significant Difference (LSD) approach with a significance level (p-value) of ≥ 0.05.

i. **Seawater**

The values obtained from seawater samples of TCBC ranged between 4.91×10^7 and 5.01×10^7 cfu/g, indicating a substantial culturable bacteria presence. This is a consistent range with findings from prior studies which have established that seawater often harbors a significant number of bacteria owing to factors such as nutrient availability, organic matter input, and water temperature [7, 19].

ii. **Mobile Ship Hull**

The mobile ship hull samples showed a significant high bacteria count, ranging from 3.90×10^9 to 3.98×10^9 cfu/g. This high count can be attributed to the continuous ship movement, which facilitates bacteria growth attachment on hull surfaces. Other studies showed similar trends with development of biofouling communities on ship hulls, resulting to amplified bacterial densities [11, 20].

iii. **Stationary Ship Hull**

Comparatively, stationary ship hulls presented a lower bacteria count, with values between 9.14×10^7 and 9.33×10^7 cfu/g. This variance could be owing to the reduced disturbance and lower nutrient exchange rates by stationary ships, which restricts bacterial colonization and growth. This outcome aligns with former research signifying that those stationary structures in maritime environments usually support lesser bacterial densities than mobile structures [21].

iv. **Sediment**

Samples obtained from sediment offered the highest bacteria count, ranging from 5.51×10^9 to 5.62×10^9 cfu/g. Abundant nutrients are known to be present in sediments, providing a stable and enabling environment for bacterial proliferation. The high bacterial counts as observed in this study are supported by the findings from other research that highlights the part of marine sediments as pools for abundant and diverse bacterial communities [22, 23].

4.1 Identification of bacteria

Cultured isolates were subjected to various biochemical tests and morphological examination to identify the bacterial isolates involved in biofouling and biocorrosion: cell morphology, gram reaction, oxidase, catalase, indole, methyl red, Voges Proskauer, motility, citrate, slant, butt, gas and H_2S production, urease, glucose and starch hydrolysis.

i. **Cell Morphology and Gram's Reaction:** Gram's reaction and Cell morphology were determined exploiting the standard procedures of Gram's staining (Crystal violet, iodine solution, alcohol (decolorizer), safranin), which exposes both the shape (e.g., bacilli, cocci) and cell wall characteristics (Gram-negative or Gram-positive) of the bacteria [24].

ii. **Oxidase Test:** The oxidase test was performed using oxidase reagent to identify cytochrome oxidase-positive bacteria [25].

iii. **Catalase Test:** The catalase test was conducted by adding hydrogen peroxide to the bacterial colony to detect catalase enzyme activity [26].

iv. **Indole Test:** The indole test was performed using Kovac's reagent for the detection of indole production from decomposition of tryptophan [27].

v. **Methyl Red (MR) Test:** The methyl red (MR) test was conducted to detect mixed acid fermentation by adding methyl red indicator to the culture [27].

vi. **Voges-Proskauer (VP) Test:** The Voges-Proskauer (VP) test was executed to detect the production of acetoin by adding VP reagents A and B to the bacteria culture [28].

vii. **Motility Test:** The motility test was conducted in semi-solid agar to observe bacterial movement away from the stab line [29].

viii. **Citrate Utilization Test:** The citrate test utilization was achieved using Simmons citrate agar to detect utilization of citrate potential as a sole carbon source [30].

ix. **Triple Sugar Iron (TSI) Agar Test:** The triple sugar iron (TSI) agar test was used to detect glucose, lactose, and sucrose fermentation, gas production, and hydrogen sulfide (H_2S) production, with observations including color change in the slant and butt, gas bubbles, and black precipitate formation [31].

x. **Urease Test:** The urease test was conducted by means of Christensen's urease agar for the urease enzyme activity detection, indicated by change of color to pink [32].

xi. **Glucose Fermentation Test:** The fermentation test for glucose was performed in phenol red glucose broth for acid production detection from glucose fermentation [33].

xii. **Starch Hydrolysis Test:** The test for starch hydrolysis was conducted by inoculating bacteria on starch agar plates and introduction of iodine solution to detect starch hydrolysis, specified by a clear zone around the bacterial growth [34]. The results obtained from the bacterial identification tests are shown below in Table 2.

Table 2: Morphological and Biochemical Identification of isolates obtained from the study

Parameter	**Isolate 1**	**Isolate 2**	**Isolate 3**
Cell Morphology	Rod	Rod	Rod
Gram's reaction	(+) *Bacillus*	(+) *Corynebacterium*	(-) *Pseudomonas*
Oxidase	(+)	(-)	(+)
Catalase	(+)	(+)	(+)
Indole	(-)	(-)	(-)
Methyl red	(-)	(-)	(-)
Voges Proskauer	(+)	(+)	(-)
Motility	Non-motile (-)	(+)	Motile (+)
Citrate utilization	(+)	(+)	(+)
Slant	Alkaline (B)	Alkaline (B)	Acid (A)
Butt	Acid (A)	Acid (A)	Acid (A)
Gas production	(+)	(+)	(-)
H_2S production	(+)	(-)	(-)
Urease	(+)	(+)	(-)
Glucose fermentation	Acid production (A+)	Acid production (A+)	No acid production (A-)
Starch hydrolysis	(+)	(-)	(-)
Identified species	*Bacillus* species	*Corynebacterium* species	*Pseudomonas* species

The bacterial isolates obtained from maritime samples as subjected to various biochemical tests and morphological examinations to identify the species involved in biocorrosion and biofouling. The results, as summarized in Table 2, reveal the presence of three bacterial isolates; *Corynebacterium* sp.**,** *Bacillus* sp. and *Pseudomonas* sp. Individual species exhibited distinct morphological and biochemical characteristics, vital for their identification and understanding of their role in the marine environment.

These findings are in consonance with other literature which describes these genera as common constituents in aquatic environments, predominantly on biofouling and biocorrosion prone surfaces [35, 36]. The positive catalase and oxidase reactions, interacting with other biochemical properties, are consistent with *Pseudomonas* and *Bacillus* species profiles, which are recognized for their metabolic diversity and resilience [37].

The presence of *Bacillus* sp., *Corynebacterium* sp. and *Pseudomonas* sp. as the identified bacterial isolates highlights their important roles in the maritime environment biofouling and biocorrosion. The varied biochemical profiles highlight their potential impact and adaptability on maritime structures.

4.2 Physicochemical composition of the Ibaka seawater and sediments

The composition of the Ibaka seawater as seen in Table 3 revealed Temperature 28^{o}C, pH for 7.36±0.025, while electrical conductivity 491.15±0.02µS/cm, Biochemical oxygen demand 22.42±0.4 (mg/kg), Chlorides 12263±124 (mg/kg) with sulphates and nitrates as 1446.67± 0.00 and 0.0836±0.001 respectively. The Ibaka Seawater composition designates favorable conditions to both biofouling and biocorrosion developments. Certain factors such as pH, temperature, chloride concentration, and biological load significantly play roles in influencing these phenomena.
Table 4 indicated pH of 5.7 ± 0.00, and temperature 24^{o}C. Electrical conductivity was recorded as 114.00 (µS/cm). The Biochemical Oxygen Demand was 5.7 (mg/kg). Sulphates was 475 ± 0.00 mg/kg. Nitrate was observed in the sediment was observed to be lesser with 0.0475 ± 0.00 as compared to that of the water sample, while phosphates was 6.65 ± 0.00 (mg/kg). Copper (Cu) was indicated to 41.838 ± 0.05 (mg/kg) while Zinc (Zn) 0.0475 ± 0.005 and lead (Pb) was 0.0095 ± 0.00. The statistical analysis of sediment content revealed significant difference at p-value < 0.05 using Least Significant difference (LSD).
These parameters are indicators of the nutrient-rich and relatively stable environment, which encourages biofouling activities and microbial growth. The slightly alkaline pH of 7.36 can influence metals and minerals solubility crucial for corrosion processes and biofilm formation [38]. High chloride concentrations (12263 mg/kg) also promote the seawater corrosiveness, affecting metal surfaces of ship hulls [39].
Composition of the sediment significantly differs from seawater, with higher concentrations and lower pH of metals and organic matter. The acidic pH (5.7) has the potential of influencing the metabolic activities, microbial community structure and, affecting corrosion processes on submerged structures and biogeochemical cycling [40]. High metals levels such as zinc (Zn) and copper (Cu) suggest possible toxicity to marine organisms and consequences for food webs bioaccumulation [41].

Table 3: Physicochemical Composition of the Ibaka Seawater

Parameter	Observations
Alkalinity	1374.3365±0.00*a
Temperature (°C)	28.0±0.000 *a
Ph	7.36±0.025 *a
Chlorides (mg/kg)	12263±124*a
BOD (mg/kg)	22.42±0.4*a
E.C (µS/cm)	491.15±0.02*a
Zn (mg/kg)	0.0931±0.002*a
Nitrates(mg/kg)	0.0836±0.001*a
Phosphates (mg/kg)	7.8185×10^{-2}*a
TOC (%)	1.767±0.15*a
Sulphates(mg/kg)	1446.67± 0.00*a

Mean Standard Error, using Least Significant Difference (LSD); p-value < 0.05. The alphabets and asterisks were used to indicate the points of relatedness of the data tested. The points with same or alphabets suggest both data is related. The difference in the data suggest points of statistical significance.

Table 4: Physicochemical Composition of the Ibaka sediment

Parameter	Sediment
pH	5.7 ± 0.00*a
Temperature (°C)	23.75 ± 0.00*c
E.C (µS/cm)	114.00*bb
BOD (mg/kg)	5.7 ± 0.00*c
Alkalinity	-
Sulphates(mg/kg)	475 ± 0.00*d
Nitrates(mg/kg)	9.5 ± 0.00*d
Phosphates (mg/kg)	6.65 ± 0.00*d
TOC (%)	0.0475 ± 0.00*aa
Cu (mg/kg)	41.838 ± 0.05*b
Zn (mg/kg)	0.0475 ± 0.005*b
Nitrates(mg/kg)	0.0475 ± 0.00*b
Cr	-
V	0.0095 ± 0.00*a
Pb (mg/kg)	0.0095 ± 0.00*b

Mean Standard Error, using Least Significant Difference (LSD); p-value < 0.05. The alphabets and asterix were used to indicate the points of relatedness of the data tested. The points with same or alphabets suggest both data is related. The difference in the data suggest points of statistical significance.

4.3 Physicochemical Composition of the Ibaka Ship-hulls

The result for the pH for stationary and mobile ship hull was 7.05 and 7.07. The Carbon content for the Ibaka stationary and mobile ship hulls was 3.68 and 3.34 (mg/kg), alkalinity 237.5 and 456.0 ppm were reported respectively. Sulphates for stationary and mobile ship hulls were 8085.93 and 1467.77 (mg/kg). TOC for stationary and mobile was 3.68 and 3.34%. Statistical analysis suggests a significant difference exists between stationary and mobile ship hull. The least significant difference was seen to identify points of significance at p-value <0.05 (Table 5). The differences in alkalinity, pH, and sulphate concentrations between mobile and stationary ship hulls reflect environmental exposure variations and biological activities. Higher sulphate and alkalinity levels in

mobile hulls may improve potential corrosion owing to microbial activity and increased ion exchange [42].

Table 5: Physicochemical Composition of the Ibaka Ship-hulls

Parameter	**Stationary**	**Mobile**
pH	7.05 ± 0.02^{a}	7.07 ± 0.02^{a}
Carbon Content (mg/kg)	3.68 ± 0.05^{a}	3.34 ± 0.05^{b}
Alkalinity (ppm)	237.5 ± 50^{a}	456.0 ± 50^{b}
Sulphates (mg/kg)	8085.93 ± 100^{a}	1467.77 ± 100^{b}
TOC (%)	3.68 ± 0.05^{a}	3.34 ± 0.05^{b}

Mean Standard Error, using Least Significant Difference (LSD); p-value < 0.05. The alphabets and asterix was used to indicate the points of relatedness of the data tested. The points with same or alphabets suggest both data is related. The difference in the data suggest points of statistical significance.

4.4 Implications of the identified bacterial species for biofouling and biocorrosion

The Ibaka Deep Sea Port identified bacterial species were *Bacillus* species, *Corynebacterium* species and *Pseudomonas* species have deep implications for biocorrosion and biofouling in nautical infrastructure. These bacteria are notorious to adhere to submerged structures, leading to biofilms formation that and biofouling. Biofouling not only increases fuel consumption, drag, and costs of vessels maintenance but also serves as invasive species reservoir, impacting ecosystem health and marine biodiversity. Additionally, these bacteria contribute to biocorrosion through corrosive metabolites production and facilitating the development of localized corrosion cells on metallic structures. This process expedites degradation of materials, compromise integrity of structures, and shortens the lifespan of nautical equipment and structures. The existence of such bacterial species requires stringent antifouling approaches, including the application of advanced coatings and biocides, to mitigate their influence on environmental sustainability and operational efficiency. Moreover, regulatory compliance with environmental standards necessitates controlling and monitoring biocorrosion and biofouling risks posed by these bacteria. Research efforts are hence vital to developing advanced solutions that minimize the environmental footprint of nautical activities while safeguarding the efficiency of port operations.

5.0 Conclusion

The data obtained from the study of highlight the bacteria counts variability across diverse maritime environments. The outcomes indicate that sediments and mobile ship hulls harbor significantly higher bacterial counts compared to stationary ship hulls and seawater. These variances are possibly influenced by factors such as availability of nutrient, movement, and environmental stability. The physicochemical parameters of seawater, sediment, and ship hulls at Ibaka provide a comprehensive understanding of the environmental conditions influencing biofouling and biocorrosion processes. Factors such as pH, temperature, chloride and sulphate concentrations, and organic carbon content play critical roles in microbial colonization and metal degradation. These insights are essential for developing effective management strategies to mitigate the adverse impacts of biofouling and biocorrosion on maritime infrastructure. The outcome of this study on bacteriological and physicochemical evaluation contributes to our understanding of microbial distribution in maritime environments, highlighting the need for targeted methods towards managing microbial contamination and biofouling. Further studies should pay attention on the specific bacterial

communities existing in the aquatic environments to advance more active biofouling management practices and to understand the ecological influences of bacterial proliferation on maritime ecosystems. Active management of biofouling is critical for operational efficiency maintenance, minimizing environmental impact to prevent corrosion. Applying combined effort of antifouling coatings, adherence to guidelines and regular maintenance can mitigate fouling issues significantly on submerged structures. Technology advancement is leading growing emphasis on sustainable development for biofouling solutions that will meet environmental standards, ensure optimal performance and marine assets longevity.

Conflict of Interests

The authors declare that there is no conflict of interest.

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