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Development of self-polishing antifouling paint with cerium oxide nanoparticle additives

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ABSTRACT

The research on self-polishing antifouling paint with cerium oxide nanoparticle additives represents a significant advancement in ship protection technology. This study aims to develop a more effective and environmentally friendly solution to prevent the growth of fouling organisms, a persistent issue in the maritime industry. Cerium oxide nanoparticles are employed to reduce the release rate of copper, the active component in many antifouling paints. The study investigates (1) the effect of cerium oxide concentration on the copper (Cu) release rate and hydrophobicity of the antifouling paint, (2) the impact of salinity on these properties, and (3) differences in the coating mechanism between paints with and without cerium oxide additives. Cerium oxide nanoparticles (50 nm) were incorporated into the paint at concentrations of 0.1%, 0.2%, 0.3%, 0.4%, and 0.5%. The coated samples were immersed in synthetic seawater and Tanjung Pasir seawater for 45 days. Results show that different CeO_2 concentrations influence the release rates of Cu and zinc (Zn). A 0.2% concentration of CeO_2 yielded the highest Cu release rate at 1.4778 $\mu g/cm^2$, while the highest Zn release rate (0.234 $\mu g/cm^2$) was observed at 0.5% CeO_2. Additionally, CeO_2 additives altered the surface characteristics of the antifouling paint, increasing its hydrophilicity as indicated by contact angle values dropping below 90°.

1. Introduction

Biofouling, the accumulation of organisms on submerged surfaces, significantly impairs vessel performance and hinders the development of the maritime industry. The development of effective coatings has become an efficient solution to this problem [1]. Antifouling paint is a type of protective coating specifically designed to inhibit the growth of fouling organisms on submerged surfaces. It functions by releasing biocides that act as toxins

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to prevent the settlement and proliferation of such organisms. Copper (Cu) is commonly used as an alternative biocide in antifouling paints [2].

In recent years, studies on copper-based antifouling paints have been conducted extensively. The efficiency of these paints can be influenced by various factors, including environmental conditions such as ocean currents, pH, salinity, dissolved oxygen, and temperature [3], [4]. Beyond environmental factors, the incorporation of additives into paint formulations also plays a crucial role. For example, the addition of 3% additives has been shown to modulate hydrophobicity and hydration properties without increasing copper release, while significantly reducing microfouling development [5]. Other research has demonstrated that graphene additives have the potential to serve as effective antifouling agents in paint formulations [6].

Recent studies involving cerium oxide (CeO_2) additives indicate that CeO_2 can promote a more homogeneous dispersion of Cu_2O in antifouling paint. Moreover, CeO_2 has been shown to restrain the rapid release of Cu_2O into seawater while maintaining its antifouling capability, thereby potentially extending the service life of the coating. Additionally, the presence of CeO_2 may assist in regulating the copper release rate in antifouling systems [7].

Therefore, this study aims to investigate the effect of varying concentrations of CeO_2 as an additive on the copper release rate and surface properties of antifouling paint. In general, the purpose of this research is to enhance antifouling efficiency. Specifically, the objectives of this study are to: (1) investigate the effect of cerium oxide concentration on the Cu release rate and hydrophobicity of antifouling paint, (2) determine the effect of salinity on the Cu release rate and hydrophobicity of antifouling paint, and (3) examine the differences in coating mechanisms between antifouling paint with and without the addition of cerium oxide.

2. Literature review

2.1. Seawater

Seawater contains many organisms that live in the environment. The salinity of seawater, whether stable or fluctuating, can affect the diversity and structure of microbial communities in the initial biofilm. This condition contributes to the type and rate of fouling formation [8]. The use of seawater systems is widely used in various industries, such as the gas and oil industry, seaside power plants, shipping, and designing industrial areas near the sea. One of the main reasons for using seawater systems in industry is as a coolant. The use of seawater systems also has problems, one of which is the corrosion that occurs. The concentration of dissolved materials contained in seawater varies depending on the location of the seawater and the time of day, as there is content carried by flow from rivers, rain, and melting ice. The most important properties present in seawater are has a high concentration of salt, sodium chloride as the largest compound, high electrical conductivity, the pH is relatively high and constant, buffering capacity, solubility for gases, where oxygen and carbon dioxide are particularly important in the context of corrosion, the number of organism compounds, the presence of marine life which can be categorized into microfouling (bacteria, slimes, etc.) and macrofouling (seaweed, shellfish, sea cucumbers, and many types of animals such as fish) [9].

Lord evaluated the impact of seawater temperature on the growth and recruitment of several cosmopolitan fouling species [10]. The results showed that higher seawater temperatures can increase the growth rate and colonization of fouling organisms. The study by [11] discusses the latest advances in marine antifouling strategies, including bioactive antifouling mechanisms and self-polishing antifouling mechanisms. This study highlights the importance of understanding marine environmental factors, such as temperature and salinity, in the development of effective antifouling strategies [11].

Seawater is often associated with its salinity level. Salinity in 1902 was defined as the total amount of solid matter (in grams) contained in one kilogram of seawater when all halides have been replaced by their chloride equivalents, when all carbonates are converted to oxides, and when all organic matter is completely oxidized. The definition of salinity was revisited when techniques to determine salinity from conductivity, temperature, and pressure measurements were developed. Since 1978, the Practical Salinity Scale defines salinity in terms of conductivity ratio [9]. An increase in salinity accelerates the fouling rate on membranes, indicating the need for antifouling designs that are specific and adaptable to high-salinity conditions, such as those in seawater systems. Suspended oxygen in seawater is highly dependent on factors such as temperature and salinity [12]. The main source of oxygen in seawater comes from sea-air exchange with oxygen from the atmosphere. But mainly dissolved oxygen comes from biological processes such as photosynthesis. Another action that can cause an increase in oxygen is the introduction of air bubbles because of wave action [9].

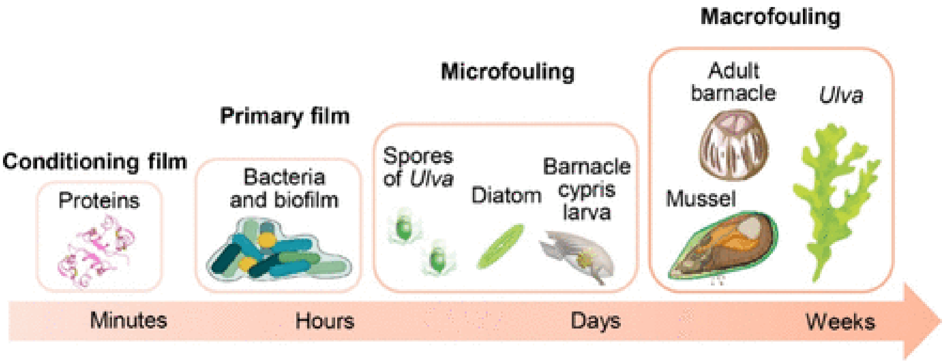


Fig. 1. Schematic of biofouling process [17].

2.2. Biofouling

Biofouling, or biological fouling, is a significant challenge in marine technology, as it reduces efficiency, increases fuel consumption, and contributes to greenhouse gas emissions from ships. This process occurs when microorganisms, plants, algae, or small animals accumulate on wet surfaces, such as a ship's hull, leading to decreased performance and structural damage as shown in Fig. 1. Biofouling is categorized into two main types: microfouling, which involves the formation of biofilms and bacterial adhesion, and macrofouling, characterized by the attachment of larger organisms such as shellfish, bryozoans, and polychaetes. Both forms of biofouling can result in substantial economic losses and adverse effects on the marine environment. For instance, biofouling on ships increases drag during navigation, leading to higher fuel consumption and elevated maintenance costs. Additionally, biofouling can accelerate corrosion on submerged artificial surfaces, further increasing maintenance expenses and fuel use. To mitigate these issues, antifouling technologies, such as paints containing specialized compounds to prevent organism adhesion, have been developed. However, the environmental impact of these chemicals must be considered, as some can harm marine ecosystems [13]. Biofouling not only impairs surface performance but also promotes corrosion of marine metal surfaces through the biological and chemical activity of biofilms [14].

Biofouling significantly influences the corrosion rate of metal materials in marine environments. Research indicates that calcium deposits on metal surfaces facilitate the adhesion of marine microorganisms. Moreover, metabolites produced by biofouling organisms can alter the physicochemical properties of metal surfaces, thereby affecting the corrosion process [15]. When a material is submerged in seawater, fouling organisms, also known as attached biota, adhere to its surface [16]. The attachment process occurs in several stages. First, organic materials are adsorbed onto the surface, forming a conditioning layer within minutes of submersion. In the second stage, within the first 24 hours, microbial cells approach and adhere to this layer, with bacteria beginning to colonize the surface. The third stage involves the arrival of secondary organisms, often attracted by chemical signals from the microbial community. In the fourth stage, invertebrate larvae (e.g., mussels or barnacle cyprids) settle, eventually forming complex macroscopic fouling communities [13]. To address marine biofouling, various strategies have been developed, including the use of toxic agents, surface patterning, and modification of surface elasticity to promote fouling release. Currently, most antifouling coatings rely on three primary approaches: incorporating biocides, designing antifouling surfaces, and applying coatings that facilitate the release of fouling organisms. These strategies aim to prevent marine organisms from adhering to surfaces or to reduce their adhesion strength, making removal easier [17].

Understanding of the corrosion rates and mechanisms associated with biofouling forces the marine industry to rely on cost- and labor-intensive mitigation measures, such as frequent scraping of metallic structures or regular assessment of protective coatings [18]. Updated understanding on the effect of biofouling on corrosion rate is needed to protect marine structures as climate change is altering seawater physiochemistry and biofouling organism distribution [19].

2.3. Antifouling

Antifouling paint, illustrated in Fig. 2, is a specialized coating designed to prevent fouling organisms from adhering to material surfaces by continuously releasing antifouling components into seawater [20]. These components, known as biocides, are substances or products used to protect materials from unwanted plants, animals, or microorganisms [21]. Tributyltin (TBT) is a commonly used biocide in antifouling paints; however, its use has been banned in several countries due to environmental concerns [22].

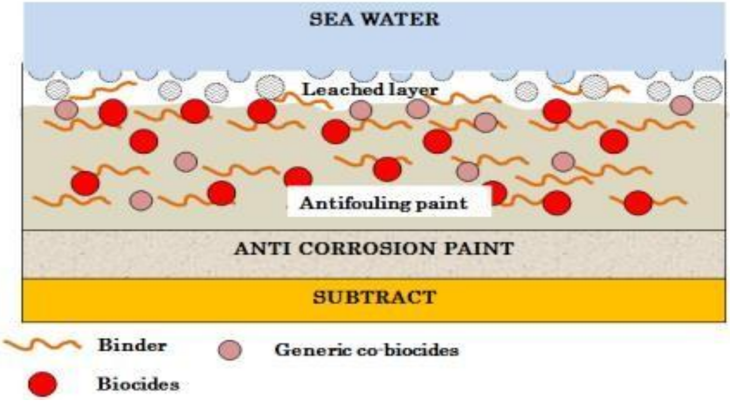


Fig. 2. Illustration of antifouling paint in seawater [3].

An alternative to TBT is copper, which serves as the primary biocide in some antifouling paints. Copper effectively inhibits the growth of various fouling organisms, including algae, bacteria, mollusks, and other marine species [3]. Both inorganic and organic copper compounds are widely used as biocides in antifouling paints. Notably, Cu_2O nanomaterials, which are metal oxides with antibacterial properties, can be synthesized easily at a low cost. When exposed to seawater, Cu_2O undergoes a reaction that releases Cu^+/Cu^{2+} ions, which exhibit biocidal activity against marine organisms. Consequently, paints containing Cu_2O are used to protect steel hulls from fouling organisms. The release of Cu^+/Cu^{2+} ions occurs through dissolution in seawater, forming oxychlorides [23].

Antifouling coatings play a crucial role in preventing corrosion on marine structures by inhibiting the accumulation of biofouling organisms, which can accelerate material degradation. Several studies have emphasized the importance of these coatings in maintaining the integrity and longevity of marine vessels and equipment [24]. According to Liang, with the rapid development of marine engineering, effective antifouling and anticorrosion technologies are essential for ensuring the safety and longevity of marine facilities [25].

Antifouling is an important strategy in marine environmental management and the maritime industry. Antifouling agents are designed to prevent the accumulation of organisms on submerged surfaces, such as ship hulls and underwater structures, which can lead to decreased efficiency and material damage. Alkyl-triphenyl phosphonium salts have attracted attention as antifouling compounds due to their ability to inhibit the growth of various marine organisms. Recent research has shown that these salts are not only effective as biocides that inhibit the growth of microorganisms, but also have potential as disruptors of quorum communication, which is an important mechanism in biofilm formation by bacteria. In addition, their ability to act as mussel repellents offers a more environmentally friendly approach compared to conventional biocides that are often toxic and damaging to marine ecosystems. By understanding the mechanism of action and environmental effects of alkyl-triphenyl phosphonium salts, researchers can develop more effective and sustainable antifouling solutions to protect marine infrastructure and support the sustainability of the maritime industry [13].

Effective corrosion protection measures can extend the service life of metallic structures and lower maintenance and repair costs in industries. Effective corrosion mitigation will help to prevent many unforeseen calamities that can result in fatality, negative social impacts, and environmental pollution. Corrosion is the degradation of materials (generally metals or alloys) or their qualities because of a chemical or electrochemical interaction with their surroundings [26].

2.4. *Antifouling self-polishing*

Self-polishing antifouling paint is a type of antifouling coating specifically designed to protect boat hulls from the growth of marine organisms, such as shellfish, algae, and mollusks. Unlike traditional paints that form a hard barrier, self-polishing paints function through a process called "ablative action," in which the outer layer gradually erodes, releasing biocides that inhibit the growth of marine organisms. This continuous ablative action helps prevent the buildup of marine organisms on the hull. The lifespan of self-polishing paint varies depending on factors such as water conditions, vessel usage, and the paint formulation. Generally, self-polishing paints last one to three seasons before requiring reapplication. The primary advantage of self-polishing paint is its effectiveness in preventing marine organism growth, which can enhance vessel performance and fuel efficiency. Additionally, self-polishing paint is relatively easy to apply and maintain, as it does not require sanding between coats. This makes it a convenient option for shipowners seeking an effective antifouling solution.

Self-polishing paint can typically be applied over other types of paint after proper surface preparation. It is crucial to follow the manufacturer's instructions regarding compatibility and preparation. Self-polishing paints can be used in freshwater, but their effectiveness may vary compared to saltwater use due to differences in marine organism growth and environmental conditions [27]. During the service process, the surface layer of self-polishing coatings comes into contact with seawater and dissolves through a hydrolysis reaction, allowing biocides to be released gradually into the water [28].

2.5. Cerium oxide

Cerium oxide (CeO_2) nanoparticles are highly effective as carriers or reservoirs for various types of corrosion inhibitors [29]. The effect of adding CeO_2 to self-polishing antifouling (SPA) paint on the copper release rate was investigated. The results showed that incorporating 0.1% by weight of CeO_2 increased the copper release rate, thereby enhancing the antifouling effectiveness of the coating [30]. The CeO_2 nanocoating demonstrated outstanding corrosion resistance, with an impedance modulus 46.9 times higher than that of the aluminum sample. This approach offers a sustainable and environmentally friendly surface modification strategy for improving the antifouling and anticorrosion performance of aluminum materials [1].

3. Material and method

3.1. Materials

In this research, the selection of materials was carried out meticulously to ensure the accuracy and reliability of the results. Each material plays a critical role in the testing and analysis process, serving as a primary medium, supporting agent, or test component. Seawater from a specific location was chosen to represent natural marine conditions, while various chemicals and solid compounds were used to prepare synthetic solutions with controlled characteristics. In addition, materials such as antifouling paint and cerium oxide nanoparticles were utilized to evaluate coating performance against biofouling and corrosion under conditions simulating the marine environment. The materials are used in this research, Seawater from Tanjung Pasir, distillated water, generic antifouling paint, cerium oxide (particle size 50 nm), HCl solution, HNO_3 solution, Anhydrous $CaCl_2$ powder, H_3BO_3 powder, KBr powder, KCl powder, $MgCl_2{\cdot}6H_2O$, NaCl, NaF, $NaHCO_3$, NaOH, Na_2SO_4, and $SrCl_2{\cdot}6H_2O$ powder.

3.2. Preparation for test samples

The test media consisted of two kinds of media, namely steel plates for SEM testing and contact angle tests and polycarbonate cylinders for spectrophotometer testing with a diameter of 6.4 cm and a cylinder length of 17.8 cm. The steel plate is cleaned of impurities such as oxide impurities by sandpaper using 200 grid sandpaper as well as to roughen the surface of the steel plate so that the paint adheres more easily. The polycarbonate cylinder was cleaned of paint residue using acetone. The clean cylinder was then immersed in a 10% HCl solution with a minimum time of 6 hours. After soaking, it was distilled water and then dried. The surface of the cylinder was then isolated by paper leaving a surface area with a height of 10 cm. The detailed procedures in this study as follows.

(a) Antifouling paint mixing.
In this study, there are four variations of antifouling paint used, namely with variations in CeO_2 content of 0%, 0.1%, 0.2%, 0.3%, 0.4%, and 0.5% CeO_2 from the total mass of the entire antifouling paint. Each paint is mixed with CeO_2 and then stirred until evenly distributed.

(b) Painting test samples.
The steel plate test media is painted by dipping the steel plate into the paint that has been mixed, namely 0%, 0.1%, 0.2%, 0.3%, 0.4%, and 0.5%, and then dried for one day. Polycarbonate cylinders were painted by brushing and the thickness was measured using a minimum wet film thickness (WFT) of 200 µm and dried for 1 day or 24 hours. After drying, remove the paper insulation from the polycarbonate cylinder.

(c) Preparation of artificial seawater solution.
This artificial seawater is made based on ASTM D 1141 – 98 [31]. The procedures that must be carried out are as follows:

1. Make 1 liter of solution no.1 by dissolving 555.6 grams of $MgCl_2{\cdot}6H_2O$, 57.9 grams of CaCl2, and 2.1 grams of $SrCl_2{\cdot}6H_2O$ with distilled water.
2. Make 1 liter of solution no.2 by dissolving 69.5 grams of KCl, 20.1 grams of $NaHCO_3$, 10 grams of KBr, 2.7 grams of H_3BO_3, and 0.3 grams of NaF using distilled water.
3. Mix 245.34 grams of NaCl, and 40.94 grams of Na_2SO_4 then dissolve using 9 liters of distilled water for the artificial seawater solution.
4. Add 100 ml of solution no.1 and 200 ml of solution no.2 to the artificial seawater solution.
5. Check the pH of the seawater solution, if the pH is less than 8.2 then add 0.1 N NaOH solution until it reaches pH 8.2.

3.3. Immersion of test samples

The test samples were immersed in different solutions to evaluate the effect of CeO_2 content. The samples were exposed to seawater with fixed pH (8.2), salinity, and temperature. The media used included synthetic seawater and natural seawater collected from Sand Cape Beach. The samples were soaked for 45 days in accordance with ASTM D6442 standards.

4. Results and discussion

This study used antifouling paint with biocides as the main ingredients—Cu_2O, ZnO, and additional CeO_2—applied to a polycarbonate cylinder and immersed in synthetic seawater and sand cape seawater for 45 days.

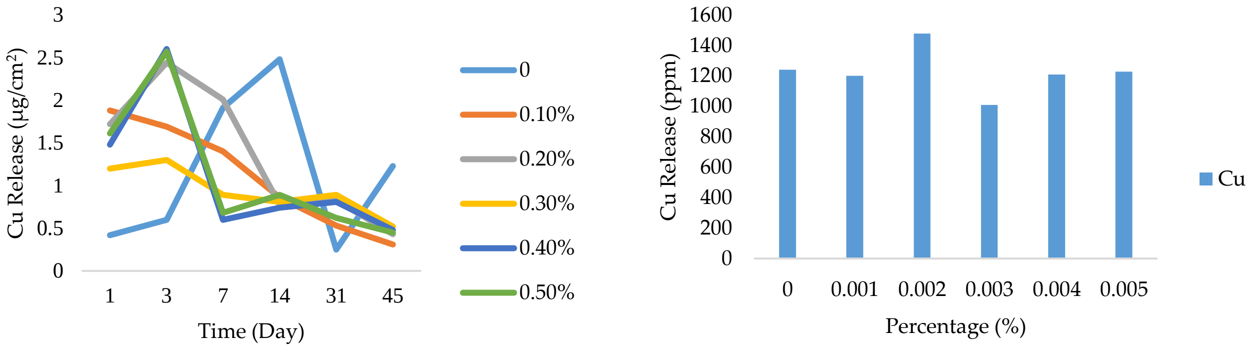
4.1. Result of copper release in antifouling paint

Before soaking in the two-seawater media, a characterization process was first carried out using conductivity, TDS, and salt meter instruments. This was done to identify possible factors that might affect the results of the study. The characterization results of the synthetic seawater solution are presented in Table 1, while the characterization results of the cape sand seawater are also shown in Table 1.

The process of collecting data on the content of Cu and Zn in synthetic seawater media and sand cape seawater is carried out through DR 1900 Spectrophotometer testing based on Standard Method 8026 (Cu) and Method 8009 (Zn). The results obtained in the DR 1900 Spectrophotometer measurement based on standard method 8026. The data results can be presented in Fig. 3(a).

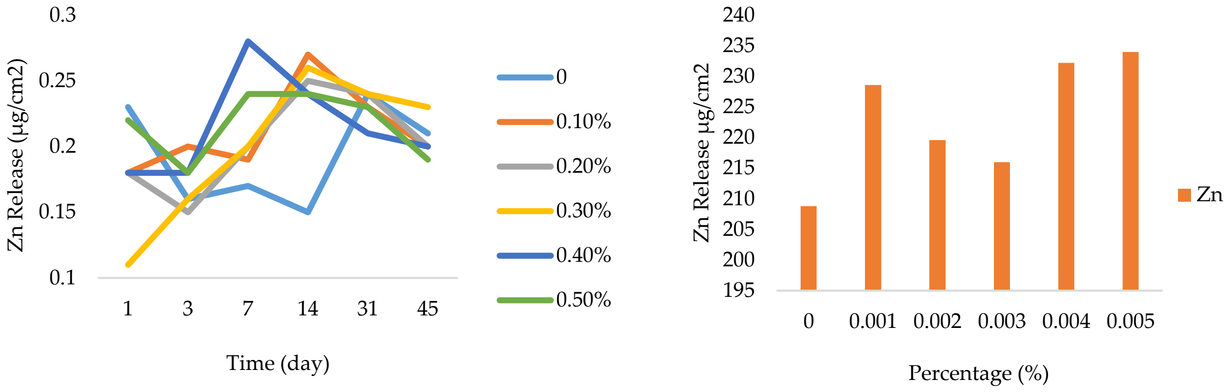
Table 1
Characteristics of synthetic seawater.

No	Parameter	Value	UoM
1	Salinity	2.99	(0/00)
2	Conductivity	49.2	(µS/cm)
3	pH	8.2	
4	Total dissolved solid (TDS)	32,800	ppm



(a) (b)

Fig. 3. Graph of Cu release over 45 days: (a) total released and (b) percentage released.



(a) (b)

Fig. 4. Graph of Zn release over 45 days in synthetic seawater media: (a) total released and (b) percentage released.

Based on Fig. 3(a), there are differences in the results of each sample variation. The highest Cu release rate occurred on day 3 with a CeO_2 concentration of 0.4% immersion and continued to decrease on the next immersion day. In Fig. 3(a) the effect of variations in the type of CeO_2 concentration used can be seen. In this study, 6 CeO_2 concentrations were used, namely concentrations of 0%, 0.1%, 0.2%, 0.3%, 0.4% and 0.5% with a size of 50 nm. The highest Cu release rate occurred in the variation of particle concentration type 0.4% variation on the 3rd immersion day. This is because of the effect on the amount of concentration used, the amount of biocide concentration that is more widely used has a greater chance to penetrate than the small concentration used, resulting in a higher release rate.

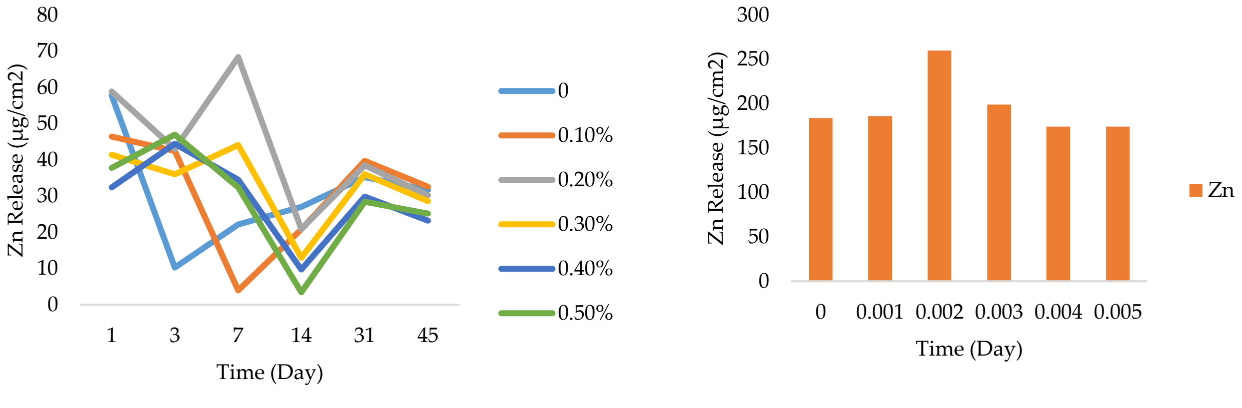
Based on Fig. 3(b), there are differences in results for each sample variation. The highest total Cu release rate occurred at a concentration of 0.2% immersion and continued to decrease at subsequent concentrations. In Fig. 3(b), we can see the effect of varying the CeO_2 concentration used. The highest total Cu release rate occurred in ZnO with a 5% variation in nanoparticle size and the lowest Cu release rate occurred in CeO_2 with a concentration variation of 0.3%. This is due to the influence on the CeO_2 concentration used.

4.2. Result of zinc release in antifouling paint

The data obtained, in addition to the Cu release rate data, include the Zn release rate data. The Zn release in synthetic seawater and Sand Cape seawater, observed after the immersion test, is derived from the ZnO content in the antifouling paint mixture. The Zn release rate data for 45 days, across samples with varying CeO_2 concentrations, are presented in Fig. 4.

Fig. 4(a) and Fig. 4(b) illustrates the release rate of zinc (Zn) ions from antifouling materials containing various concentrations of cerium oxide nanoparticles (0% to 0.50%) in synthetic seawater. The data show that at higher concentrations of cerium oxide (0.30% to 0.50%), the Zn release rate was lower than at lower concentrations or without cerium oxide (0%). This suggests that cerium oxide inhibits the release of Zn ions into the environment. During the first 14 days, all samples exhibited fluctuations in Zn release, but from days 31 to 45, higher concentrations of cerium oxide stabilized Zn release, as evidenced by reduced fluctuations. The addition of cerium oxide to antifouling materials appears to promote controlled, gradual Zn release, particularly at concentrations of 0.30% and above. This may result from interactions between cerium oxide and the coating matrix, which slow the diffusion rate of Zn ions. These findings indicate that cerium oxide nanoparticles may be a key component in enhancing the stability of antifouling materials, reducing release into the environment, and prolonging antifouling effectiveness. This research is relevant for minimizing the environmental impact of metal-based coatings.

Several studies support these findings. A study published in *Scientific Reports* demonstrated that cerium oxide (CeO_2) nanoparticles can reduce fouling and improve material stability by interacting with the coating matrix and decreasing the diffusion rate of metal ions [32]. However, Fig. 4(b) shows that adding cerium oxide nanoparticles to antifouling paint affects Zn release in synthetic seawater. At higher concentrations of cerium oxide nanoparticles, Zn release initially increases to a certain extent before stabilizing. This suggests that cerium oxide nanoparticles influence the Zn release mechanism in antifouling paints, with implications for surface protection and fouling control.



(a) (b)

Fig. 5. Graph of Zn release over 45 days in natural seawater media: (a) total released and (b) percentage released.

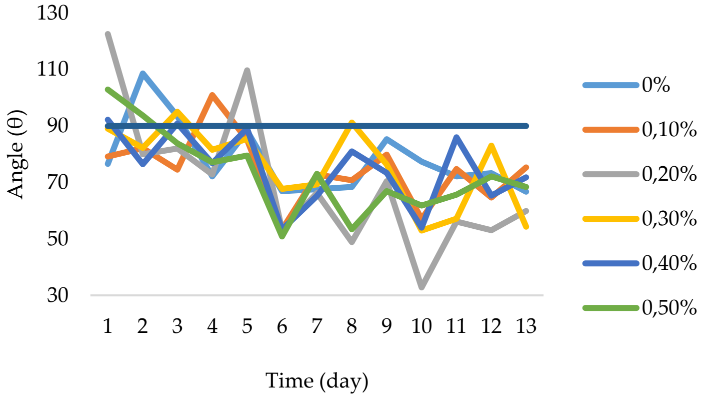


Fig. 6. Graph of contact angle results of CeO_2 concentration variations.

Fig. 5 shows that the total Zn (zinc) release in a natural seawater medium is influenced by the addition of cerium oxide nanoparticles to antifouling paint. The Zn release peaked at a cerium oxide nanoparticle concentration of 0.002% but decreased or stabilized at lower levels when the nanoparticle concentration was increased further (0.003% to 0.005%). This trend suggests a saturation effect, where higher concentrations of cerium oxide nanoparticles exceed the optimal capacity to influence Zn release. The stability of Zn release at higher nanoparticle concentrations may indicate that cerium oxide nanoparticles help regulate the release of active ingredients, providing a more controlled and effective protective effect in a natural seawater environment. This finding aligns with the study by [33], which demonstrated that additives could control the release of active ions to improve efficiency and reduce environmental impact, and with Selim et al. [34], which showed that cerium oxide nanoparticles stabilize the protective layer and control the release of active ions. Thus, adding cerium oxide nanoparticles can optimize Zn release, enhance antifouling effectiveness, and minimize the environmental impact of excessive active ingredient release.

4.3. Result of contact angle test

Contact angle testing produces results in the form of photographs of synthetic seawater solution droplets formed on the surface of steel samples that have been applied with antifouling paint. Which can visualise the angle changes that occur on the 0th day of immersion to the 45th day of immersion and can be seen in Fig. 6. Based on the contact angle data obtained on antifouling paint samples with varying concentrations of CeO_2 used, it can be seen in Fig. 6 that there are differences in the results of contact angles in each variation of CeO_2 concentration used in antifouling paint. Based on Figure 8, the contact angle continues to decrease along with the immersion time, where the highest contact angle occurs on day 0, which means that the test is carried out before immersion in synthetic seawater and decreases on the 21st day of immersion. In Fig. 6 the sample with a concentration variation of 0.2% CeO_2 50nm has the lowest contact angle compared to samples with other variations on the 35th day of immersion where a contact angle of 32.82o is obtained. It is known that if the contact angle value is less than 90°, it can be said to be hydrophilic.

Changes in contact angles that occur due to the influence of the concentration of CeO_2 used, where along with the increase in the concentration of CeO_2 used, the contact angle is getting higher, this is similar to research conducted by Khan et al. [35] revealed that increasing the concentration of CeO_2 increases the contact angle with a value of 76.64^0 to 122.59^0. The same thing happens to the contact angle results obtained on antifouling paint samples with varying concentrations. Fig. 6 can be seen that the contact angle continues to decrease along with the immersion time, the highest contact angle occurred on day 0 which means that the test was carried out before immersion in synthetic lat water solution and decreased on day 14 of immersion. In Fig. 6 it can also be seen that the sample continues to decrease along with the increase in CeO_2 concentration used in antifouling paint. The sample with 0.2% CeO_2 added has the lowest contact angle compared to samples with other variations on day 14 of immersion where a contact angle of 32.82^o is obtained. It is known that if the contact angle value is less than 90°, it can be said to be hydrophilic [36].

5. Conclusions

The research on the effect of adding cerium oxide (CeO2) nanoparticles as a booster in antifouling paint demonstrates that:

1. Variations in CeO_2 concentration influence the release rates of Cu and Zn. A CeO_2 concentration of 0.2% yields the highest Cu release rate of 1.4778 $\mu g/cm^2$, while a 0.5% concentration results in the highest Zn release rate of 0.234 $\mu g/cm^2$, compared to other concentrations (0.1%, 0.3%, and 0.4%).
2. The addition of CeO_2 enhances the hydrophilic properties of the antifouling paint surface, as indicated by a contact angle below 90°, which supports biofouling resistance in synthetic seawater and Tanjung Pasir seawater media.

Future studies should explore a broader range of CeO_2 concentrations to optimize Cu and Zn release rates while maintaining antifouling efficacy. Long-term testing in diverse marine environments is needed to assess the durability and performance of CeO_2-enhanced antifouling paint under varying conditions. Additionally, comprehensive surface characterization, including roughness and mechanical stability, should be conducted to further understand the role of CeO_2 in enhancing hydrophilicity. Direct biofouling resistance tests against specific marine organisms and environmental impact assessments of Cu and Zn release are also recommended to ensure practical and sustainable applications.

Declaration statement

Bening Nurul Hidayah Kambuna was responsible for the overall research design, supervision, and final review of the manuscript. **Yanyan Dwiyanti** and **Arini Nikitasari** contributed to data analysis, literature review, and manuscript writing. **M. Imam Prasetyo** and **Aditya Rahman** final-year undergraduate student, assisted in laboratory work, sample preparation, and data collection under the supervision of the lead researcher.

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Disclosure statement

The authors declare no conflicts of interest.

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Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article or its supplementary materials.

AI Usage Statement

Generative AI and AI-assisted tools were used to enhance the language and readability of this manuscript. The authors have reviewed and revised all AI-generated content to ensure its accuracy and alignment with the research. The authors remain fully responsible for the work's scientific content, conclusions, and integrity, and disclose the use of AI to ensure transparency and adherence to publisher guidelines.

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