BLUE-ANTIFOULING: SUSTAINABLE INNOVATION AGAINST BIOFOULING IN NAVAL EQUIPMENT

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Abstract

Seaweed is a natural source of alginate, a substance composed of alginic acid units and calcium ions, known for its gelling capacity. This material induces self-association, forming stable micelles that create a hydrated layer on the surfaces of vessels, providing resistance to biofouling. The hydrogel can be crosslinked through physical mixing or by combining hydrophilic and hydrophobic polymers, based on the principles of ecological chemistry. Blue-antifouling represents an innovation in its applicability, being a high-performance non-biocidal product that uses hydrodynamic principles to prevent biofouling in submerged structures. In addition, monitoring macroalgae bloom areas can boost the promotion of the bioeconomy, contributing to the advancement of research in the areas of Marine Science and Technology.

Keywords

Biofouling, Alginate Gel, Antifouling, Marine Equipment Protection.

1. INTRODUCTION

Marine biofouling not only compromises the efficiency of vessels, but is also exacerbated by ballast water, which facilitates the invasion of exotic species and causes serious damage to marine ecosystems (Pereira et al., 2021). The inappropriate use of ballast water can result in the introduction of non-native organisms into new environments, altering local biodiversity and causing ecological imbalances (Silva & Almeida, 2020). In addition, biofouling directly impacts vessel engines, increasing component wear and reducing the efficiency of propulsion systems (Santos et al., 2019). This increased resistance to movement leads to higher fuel consumption, increasing operating costs and the emission of polluting gases (Oliveira & Costa, 2018). In response to these challenges, scientists have intensified research and development of innovative solutions (Lima et al., 2022). The study in question focuses on the viability of Blue-antifouling, an alginate hydrogel that reduces the adhesion of fouling organisms, offering an ecological alternative to conventional antifouling paints (Cardoso, 2024). This material contributes to the mitigation of environmental impacts and promotes sustainability in navigation, preventing the maintenance of vessel equipment, presenting a more responsible and efficient solution to the problem of biofouling (Andrade et al., 2023). This work explores the potential of alginate hydrogel as an antifouling, highlighting its essential role in operational efficiency and in mitigating the environmental impacts associated with biofouling.

2. GENERAL OBJECTIVE

Develop a sustainable and innovative alternative for marine antifouling, focusing on improving the efficiency of operational equipment and mitigating the environmental impacts associated with biofouling.

2.1. Specific Objectives

- Assess the availability and quality of seaweed in the South Atlantic region to identify effective sources of alginate for the production of antifouling agents.
- Develop the production process for Blue-antifouling, an alginate hydrogel, ensuring that it is environmentally sustainable and effective against biofouling.
- Test the application of Blue-antifouling in marine equipment, evaluating its performance in preventing biofouling and its ability to reduce fuel consumption and the emission of polluting gases.

3. A SUSTAINABLE AND INNOVATIVE ALTERNATIVE AGAINST BIOFOULING

Brown algae, abundant in the oceans, are a rich source of alginate, a polysaccharide with gelling and antioxidant properties widely explored in several biomedical and industrial applications (Cardoso, 2024). Alginate, extracted from these algae, has the unique ability to form hydrogels when combined with other components, standing out as a promising candidate for the development of anti-fouling technologies (CPA Cintia, 2024). Studies demonstrate that alginate can form stable hydrogels that, when applied to submerged surfaces, offer resistance to the adhesion of marine organisms, preventing biofouling (Draget et al., 2005; Wei et al., 2024). The combination of alginate with hydrophobic polymers, such as polydimethylsiloxane (PDMS), results in a high-performance material for use in marine environments. PDMS, known for its hydrophobic properties and wear resistance, acts as a physical barrier, while alginate provides a biocompatible matrix that prevents the attachment of marine organisms. Recent research has shown that this combination is not only effective in preventing fouling, but also minimizes environmental impacts, offering a viable alternative to traditional antifouling paints that contain harmful biocides (Andrade et al., 2023; Johnson & Smith, 2022). In response to the challenges posed by biofouling and the negative impacts of ballast water, the scientific community has intensified the development of innovative solutions. One such solution is Blue-antifouling, an alginate hydrogel that, by reducing the adhesion of fouling organisms, offers an environmentally friendly alternative to conventional antifouling paints (CPA Cardoso, 2024). This study investigates the feasibility of using this material to provide ecological and operational benefits, aligning with sustainability and environmental conservation goals. The implementation of these emerging technologies, such as the combination of alginate and PDMS, can improve vessel efficiency, reduce fuel consumption, mitigate pollutant gas emissions and contribute to the protection of marine ecosystems (CPA Cintia, 2024). Continued research in this area is essential to develop solutions that balance the operational maintenance needs of navigation with the preservation of the marine environment, promoting a sustainable and responsible bioeconomy.

4. SCIENTIFIC AND TECHNOLOGICAL ASPECTS OF ALGINATE AND PDMS

Alginate, a natural and biodegradable polymer, forms a gel in the presence of cations such as calcium, providing a base structure for the antifoulant (Draget et al., 2005). This ability to form gels, coupled with its biodegradability, offers a significant environmental advantage if the product degrades in a controlled manner (Lee et al., 2014). The adhesion of alginate to submerged surfaces can influence the durability of the antifoulant, a crucial aspect for its long-term effectiveness. PDMS, on the other hand, is a highly hydrophobic polymer, which reduces the adhesion of marine organisms and creates a surface where it is difficult for organisms to attach (Liu et al., 2017). Its good wear resistance can extend the life of the antifoulant. Crosslinking alginate with calcium chloride creates a three-dimensional network, important for the mechanical integrity of the antifoulant (Draget et al., 2005). The interaction between alginate and PDMS can affect gel formation and the distribution of hydrophobic properties, and ensuring homogeneity in the mixture is crucial for product efficacy (Kumar et al., 2020). Antiscalant efficacy can vary based on the amount of PDMS in the mixture and the ability of the alginate gel to adhere to the substrate and resist wear (Wei et al., 2024). Field testing is essential to evaluate performance under real-world conditions and determine durability and resistance to biofouling over time (Johnson & Smith, 2022). The use of biodegradable materials, such as alginate, can benefit sustainability, but it is crucial to evaluate the total environmental impact of the product, including the effect of additives such as natural antimicrobial agents and nanoparticles (Andrade et al., 2023). Furthermore, the application method and surface preparation where the antiscalant will be applied influence efficacy. Clean and well-prepared surfaces improve product adhesion. Control of curing time and environmental conditions (temperature, humidity) during antifouling application and curing is critical (Lee et al., 2014). Consistency in formulation and application is vital, as small variations can significantly affect antifouling performance. Although the combination of alginate and PDMS offers a promising approach, rigorous testing is essential.s para garantir a eficácia e avaliar o impacto ambiental do produto (Liu et al., 2017; Kumar et al., 2020).

5. METHODOLOGY APPLIED TO SCIENTIFIC RESEARCH

This study adopts a mixed-methods approach, combining qualitative and quantitative methods, to investigate the effectiveness and sustainability of Blue-antifouling. The methodology is structured in three main phases:

A. **Seaweed Data Collection and Analysis:** A detailed assessment of the availability and quality of seaweed in the Atlantic Ocean is carried out, focusing on the extraction of alginate. This phase includes partnerships with research institutions and companies specializing in biotechnology to ensure the acquisition of high-quality seaweed. The alginate hydrogel is developed and optimized in the laboratory. The formulation is adjusted to maximize the effectiveness of the antifouling and minimize environmental impacts.
B. **Tests and Evaluations:** Laboratory tests are carried out to evaluate the physicochemical properties of Blue-antifouling, including its ability to form hydrogels and its resistance to the adhesion of marine organisms. In collaboration with companies in the maritime sector, field trials are conducted to evaluate the effectiveness of Blue-antifouling under real-world conditions of use. These tests measure the reduction of biofouling, the efficiency of naval equipment and the impact on fuel consumption and pollutant gas emissions.
C. **Environmental and Operational Impact Analysis:** Data collected from field trials are analyzed to assess the effectiveness of Blue-antifouling in terms of biofouling reduction and its effects on vessel performance. The analysis includes comparison with traditional antifouling methods. Based on the results, adjustments are made to the formulation and application of Blue-antifouling to improve its effectiveness and sustainability. The results are discussed in terms of implications for the marine bioeconomy and sustainable shipping practices.

5.1. The Art of Sailing: Nautical Practices and Professional Training

The research was conducted using a qualitative method that integrates knowledge acquired in Professional Maritime Education (EPM). The nautical instructor shares her sailing experiences, highlighting factors that impact the performance of boats and jet skis. Her training includes:

- Postgraduate degree in Physical Education.
- Seamanship training from the BRAZILIAN Navy.
- International Master's degree in Marine Science and Technology.
- Specialist in Marine Sciences.
- Postgraduate degree in Marine Biology.
- Aquatic rescue and titles, such as South American champion in aquatic rescue.
- Certifications in several areas of seamanship and featured on the program "O Bom Marinheiro", where she was ranked among the three best sailors in Brazil, using this platform to collect data for the research.

5.2. The Influence of Giants: Data from the Nautical Sector

In the 2023/2024 biennium, data was collected in collaboration with some of the main companies in Brazil, which include:

- OKEN YACHTS: Specialized in yacht design.
- VOLVO PENTA: Leader in energy solutions for the maritime sector.
- FIBRAFORT BOATS: Largest boat manufacturer in South America.
- STEP ON BOARD: The most prominent nautical architecture firm in Brazil.
- AZIMUT: Famous brand for its luxury yachts.
- PROPSPEED: Reference in antifouling coatings.

This data was essential to understand the trends and innovations in the contemporary nautical sector.

6. SUSTAINABLE SOLUTIONS: INNOVATIVE FORMULA AND METHOD

6.1. New Application Approach

1. Clean the surface with a dry cloth or tissue.
2. Apply a thin layer of clear coat with a brush.
3. Allow to dry for at least 8 hours before submerging the boat in water.

6.2. Antifouling Composition

Sodium Alginate

- Chemical Formula: $(C_6H_8O_7)n$
- Gel former, stabilizer

Polydimethylsiloxane (PDMS)

- Chemical Formula:$(C_2H_6OSi)n$
- Hydrophobic polymer: non-stick and low friction properties.

6.3. Preparation Method

- Preparation of Alginate Gel: Dissolve sodium alginate in distilled water to a concentration of 1-2% (w/v). Stir well to ensure complete dissolution and to avoid the formation of lumps. Sodium alginate forms a gel when interacted with a crosslinking agent.
- PDMS preparation: Use a PDMS mixture (such as Sylgard 184) composed of two components: the monomer and the catalyst. Mix the PDMS monomer with the catalyst in the ratio recommended by the manufacturer (usually 10:1).
- Mixing of Components: Add the prepared PDMS to the sodium alginate gel in a 1:1 ratio (volume/volume). Stir the mixture until a uniform solution is obtained. The PDMS will provide a hydrophobic layer that prevents the adhesion of marine organisms, while the alginate provides the gelling base and adhesion to the substrate.

- Addition of Crosslinking Agents: Add 0.1-0.5% calcium chloride ($CaCl_2$) solution to the alginate gel to promote gel formation. Stir gently until the gel begins to form. The calcium chloride interacts with the alginate to form a three-dimensional network.
- Antifouling Curing: Pour the mixture into molds or apply directly to the desired surface. Allow to cure for 24-48 hours at room temperature to ensure that the alginate gel and PDMS are fully polymerized and stabilized.

6.4. Additional Options

- Natural Antimicrobial Agents: Adding natural extracts with antimicrobial properties, such as aloe vera extract or essential oils (e.g., neem oil), may offer additional protection against biofouling.
- Nano-Silica Particles: Incorporating nano-silica (SiO_2) particles can improve non-stick properties and wear resistance.
- Hydrophobic Additives: Adding small amounts of hydrophobic additives such as graphene and carbon nanotubes can further improve the effectiveness of the antifouling.

6.5. Simplified Chemical Formula

- Sodium Alginate (1-2% in water)
- PDMS (Prepared from monomer and catalyst, 1:1 with alginate gel)
- Calcium Chloride (0.1-0.5% for crosslinking)

6.6. Additional

- Antimicrobial natural extract (optional)
- Nano-silica particles (optional)
- Hydrophobic additive (optional)
- Pigments (optional)

This formula and method provide a solid foundation for the development of an innovative antiscalant, leveraging the unique properties of alginate and PDMS. The efficacy and science behind an alginate and PDMS-based antiscalant involve several important considerations and testing is required.

7. IMPACTS OF ANTI-FOULING SOLUTION ON NAUTICAL PERFORMANCE

The experiments showed that the antifouling solution was effective in reducing biofouling by creating a protective film on the metal parts of the vessels. The tests indicated that:

- A reduction in the vessel's friction on the water surfaces was observed;
- The need for periodic engine maintenance was reduced;
- There was a reduction in fuel consumption, improving performance.

The innovative application technique provided a smooth surface on the vessels, resulting in improved propulsion system efficiency. In addition, the protection provided to the engine contributed to reducing vibrations and noise, evidencing an average fuel saving of 10% over the course of a year, although this variation depends on the use and size of the vessel. Biofouling on the transducers was also reduced, ensuring signal accuracy. The underwater lights, protected by the bioproduct, maintained their operating conditions, since conventional antifouling paints are not suitable for these surfaces.

8. FINAL CONSIDERATIONS

The use of alginate as an antifouling base offers an environmentally sustainable alternative to traditional biocide-based antifoulings. The combination of hydrophilic and hydrophobic polymers improves resistance to biofouling and extends the life of equipment. According to Cardoso (2024), navigation tests indicated that an antifouling made with gel provides a smooth surface on the live works of vessels, reducing friction and fuel consumption by up to 10%. The gel-based product has demonstrated effectiveness in protecting critical components, such as propellers and underwater lights, without compromising the clarity of images generated by transducers. Furthermore, as discussed by Wei et al. (2024), organofunctional silicone polymers, such as polydimethylsiloxane (PDMS), have excellent dielectric properties, optical transparency, and resistance to aging. However, Monteiro (2009) emphasizes that, due to its low mechanical properties, it is crucial to include a reinforcing agent to improve the performance of these polymers. Silica, commonly used as a reinforcing agent, is found in solid materials and living organisms, such as algae, and its incorporation into polymers such as PDMS significantly improves their mechanical properties, making them more resistant and durable. Alginate, a polysaccharide composed of β-D-mannuronyl and α-L-guluronyl (Chin et al., 2015), has been studied as a sequestering agent for toxic metals. Its ability to modify properties such as rheology, water binding capacity, emulsion stability and film formation is widely recognized (Kashima et al., 2012). In the presence of divalent cations, alginate forms a gel through ionic crosslinking, characterized by strength, durability and dimensional stability. The alginate extraction process, as described by Monteiro (2009), involves ion exchange of algae tissues, followed by neutralization and solubilization of alginic acid. After separation processes, such as flocculation and filtration, sodium alginate is precipitated and dried (Draget et al., 2000). Finally, the combination of the compounds studied, as pointed out by Wei et al. (2024), results in excellent antifouling properties, demonstrating effectiveness in combating protein, bacterial and microalgal fouling. Biotechnological resources have shown promise in protecting against biofilm formation and corrosion, contributing to the maintenance of naval equipment and sustainability in the sector.

You are the lord of the seas and winds, of the earth and the stars.
You are the lighthouse, the light that never goes out.
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Lord, you taught me the lesson of the waves, each retreat was an effort to move forward. You are the seas, the wind, the earth and the stars. You are the lighthouse, the light that never goes out!

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