ASSESSMENT OF SHIP FOULING: FORMATION, PREVENTION AND ENVIRONMENTAL IMPACTS

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1. **ABSTRACT:** This research investigates The effects of biofouling on fuel consumption and environmental impact. The influence of biofouling on the ship's hull from both an environmental and economic standpoint, as well as the requirement for new, cutting-edge antifouling technologies to meet future demand. The study reveals the various types of anti-fouling paints under the two main mechanisms self-polishing copolymers (SPCs) and fouling release coatings (FRCs) that were developed following the 2001 Tributyltin (TBT) ban. These mechanisms increased pressure on paint manufacturers to create an effective substitute for TBT-based paint as well as on shipping companies to find the most effective anti-fouling systems. Through Strength Weaknesses Opportunities Threats (SWOT) analysis, the study presents a methodology to help shipping companies choose the most effective anti-fouling system among several options. The outcome reveals the strengths and weaknesses of the potential anti-fouling systems.

2. INTRODUCTION

Biofouling is a sophisticated activity governed by physical and chemical properties. Biofilm is a term that refers to microbial life in aggregates. At solid-liquid, liquid-air, and solid-air interfaces, biofilms can form. Most microorganisms have the ability to form biofilms, and almost always microorganisms on Earth live in such aggregates ***(Costerton et al., 1987)***. They all share the fact that the organisms are embedded in a microbial-derived matrix composed of extracellular polymeric substances (EPS). EPS is primarily composed of polysaccharides and proteins, which combine to form hydrogel matrices **(Flemming, 2002).** These are some factors which govern the biofouling process, substratum pre-conditioning, biofoulers cell surface features, interface properties, ability to secrete EPS, cellular transport, interspecies relationships, nutrient availability, a moderate composition, the existence of inorganic matter, hydrodynamic conditions, and the presence of antifouling agents **(Hadfield, 2011).** When the no-fouled structure is immersed in seawater, a molecular layer of organic molecules will attach to the structure **(Callow and Callow, 2011),** subsequently, the macro- and micro-biofoulers may attach and settle, creating biofouling formations that live in the ship's hull.

3. FUNDAMENTALS OF BIOFOULING

3.1 Settlement

Finding and attaching to a suitable surface is one of the most crucial processes for a biofouling organism **(Wilson & Hansson, 2015).** Settlement is the process of locating an acceptable surface, exploring, evaluating, and contacting that surface **(Durr, 2010).** Considering that the weakest link is settlement in the chain of biofilm formation, it is critical to eliminate biofouling in its early phases **(*Dargahi et al*., 2014).** According to **Allison (2003),** a few hours after the surface is immersed in seawater, micro and macro biofouling covers the surface, with macro fouling being built on top of micro fouling. Regarding the micro biofouling lifespan, micro-biofilm production may be faster, and a shorter lifecycle leads to a dense and quick-growing biofilm **(Wilson & Hansson, 2015).** The biofilm substrate is mostly colonized by bacteria, where they multiply and excrete their attachment sticky matrix, permitting a resilient and stable micro-biofilm community to form **(Dobretsov & Qian, 2002).** The varieties of colonized biofouling are determined by the organisms' existing environment. Biofouling creation begins with microfouling, such as bacterial cells, and progresses to macrofouling, such as barnacles **(Antunes, 2010).** Competition for essential life needs such as nourishment, aerobic conditions, space, and light, are responsible for the variety of species found in biofilm, which are intensely competing for the few resources available. To explain, the process of photosynthesis that involves using oxygen and carbon dioxide creates a strong vertical redox gradient that stratifies the biofilm community cells, confining aerobics to the upper levels and an-aerobics to the lower levels **(Manzo & Massanisso, 2014).**

3.2 Extra polymeric substance EPS deposition

The EPS matrix has a sticky texture and intensely moistened, and it is largely made up of polysaccharides that are linked together with a variety of proteins, humic compounds, nucleic acids, glycoproteins, and phospholipids **(Daims & Wagner, 2007).** The extracellular matrix "slime" is essential for bacterial biofilm attachment and operation **(Fazi & Di Pippo, 2014).** Nature's EPS texture enfolds and receives the microorganisms forming the biofilm, allowing the proliferated colonies to be stable, enabling cells to metabolize, reproduce, and connect more efficiently, resulting in a functional stable microbial community that makes little use of its stored energy ***(Amann et al., 1995).*** Furthermore, EPS protects against heavy metals, harmful chemicals, and predator grazing. Finally, biofilms are a network of microorganisms encapsulated in a matrix that occupies a ship's hull and devices, generating a highly distinct architecture that mimics waves, ridges, and mushrooms **(Manzo & Massanisso, 2014).**

3.3 Attachment

On more rough hydrophobic surfaces that have first been preconditioned with a molecular coating, an attachment will become more stable. The adjacent environmental conditions of water temperature, flow velocity, and even the amount of nutrients can all have an effect on the strength of the attachment **(Simões & Simões, 2010).** After settling on the surface, microorganisms begin to release EPS, which supports their stability and proliferation, leading to the formation of a full biofilm ***(Landoulsi et al., 2011).*** Therefore, chemical organics such as proteoglycans, polysaccharides, and glycoproteins adhering to the hull, the adherence and settlement of biofoulers can occur without molecular film formation **(Cooksey, 1995).** Biofouling cell surface features, extracellular components, and the ability of micro-organisms to create sticky EPS give them a competitive advantage in a mixed population

(*Simões et al., 2007*). According to **Ralston and Swain (2011)**, micro-organisms cannot settle on ultra-smooth surfaces. Surface energy and texture are the two most important surface features that influence microorganism adhesion. The surface energy is one of the factors that contribute to the complexity of the marine fouling problem. To elaborate, bryozoans and barnacles prefer to connect to the surface with varying degrees of energy, but diatoms and the green algal Ulva have opposing adhesion strengths depending on surface wettability **(Wilson & Hansson, 2015).**

Furthermore, the attachment area theory indicates that when there are suitable attachment sites on both the microorganism and the surface, the solid attachment is increased. In the microscale domain, organisms with attachment sites larger than the micro texture scale will show decreased adhesion; conversely, organisms with attachment points smaller than the micro texture scale will show enhanced adhesion strength. **(*Scardino et al*., *2006, 2008*)**.

In terms of energy efficiency optimization, the shipping industry is dominated by economics, compliance, and demands. However, the shipping industry's adaptation to technical and operational advancements has been relatively slower. Because of the various effects such as weather, trim, fouling, and ocean currents, this slow adaptation is attributed to uncertainty about the integrity and quality of data gathered from the shipping industry. Although there is no standard method for forecasting how much fouling causes performance degradation in service other than monitoring the speed-to-power relationship **(Townsin, 2003).** As the number of fouling on the hull increases, the ship resistance and fuel consumption soars, which directly raises ship operational bill. The early phases of biofilm or slime fouling are often ignored, nevertheless up to 20% greater fuel consumption can be shown during the first years of fouling on a ferry ***(Hakim et al., 2017).***

Managing biofouling is a crucial step toward increasing a ship's energy efficiency. Furthermore, biofouling treatment is critical for ship safety since clogged seawater cooling systems and intakes perform inefficiently. Vessels with unclean hulls consume significantly more fuel than clean ones, and these increased fuel expenditures frequently outweigh the price of hull maintenance efforts. The best approach for vessel owners to comply with the International Maritime Organization (IMO) rules is to do continuous hull maintenance using best practices. Biofouling management is a useful vector on many levels; it protects the marine ecosystem by reducing the spread of aquatic invasive species. Furthermore, it reduces CO_2 emissions from ships, which contributes to mitigate the effects of global warming. Furthermore, it assists ship operators in saving costs because fouling increases the energy required to propel the vessel forward, resulting in increased fuel consumption, and with rising fuel prices, everything that can lead to excessive fuel use is targeted by ship owners. Managing biofouling also helps to enhance ship speed, which is critical for Roll-on/roll-off (Ro/Ro) passengers to fulfil their schedule **(Desher, 2018).**

Biofouling management is a key vector that has the potential to significantly reduce ship fuel use and thus CO_2 emissions. As a result, it is vital for the various players in the marine industry, beginning with the IMO Member States and their leaders, to strengthen this area. There is currently no dispute about the role of Green House Gases (GHGs) in global warming and their harmful impact on the environment and global sustainability. GHGs are thus a very significant issue that requires immediate attention at all levels **(Desher, 2018).**

4.The evolution of anti-fouling system types

The period before the Anti-Fouling System (AFS) convention yielded early records of fouling control and many anti-fouling materials, including lead sheets, lime, arsenals, and oil diluted with sulfur and copper **(Stebbing, 1985).** Due to the fact that TBT has become one of the most effective and economical ways of releasing the hull fouling particularly after the revolution of chemical industry, by 1960s, it has resulted in being the most widely used biocide in the antifouling system **(Evans, 1970).**

The maritime industry raised several concerns, including whether alternative paints will function as well as TBT-based paint with both financial and environmental implications. Concerns about the environmental impact stemmed from the question of whether effective alternatives might stop hull fouling, which happens when invasive organisms are controlled from migrating to new environments. Furthermore, from an economic standpoint, shipping companies have questions about how effective the alternatives are in preventing fouling and reducing paint costs. Fouling is associated with fuel oil consumption, intervals between dry docks, off-hired time, and paint lifetime.

Based on the above evidence the paint industry has been compelled to develop multiple options to address these factors, posing difficulties and uncertainties for shipping companies while deciding the most compatible anti-fouling system among these different varieties

4.1 Paints with biocidal anti-fouling properties

Include at least one active ingredient (biocides), such as copper, that regulate or stop the growth of organisms **(EU, 1998).** Copper was chosen as an example, because of its effectiveness as an active ingredient in the management of many biofouling organisms, the necessary leaching frequency of copper to stop barnacle fouling is 10 µg/cm^2/day, but 20 µg/cm^2/day is needed to stop diatoms. This is an indication figure rather than an absolute **(Finnie & Williams, 2010).**

4.2 Free association paint

When TBT is applied as a biocide, it is released by contact leaching and will eventually leak out of the coat when it comes into touch with water. This uncontrollable leaching rate will cause the coating layer to quickly disappear. Therefore, TBT-based paint is developed in a second phase **(Champ & Pugh, 1987).**

4.3 Ablative or Copolymer depletion paint (CDP)

This enhanced paint solubility mechanism, which relies on hydration or dissolving as a form of bond breakage, is the result of uncontrolled leaching. It is likewise a soluble matrix paint, with an estimated 36-month coating lifespan. Over time, the coating thickness will shrink ***(Yebra et al., 2004).***

4.4 Tributyltin self-polishing copolymer (TBT-SPC paints)

The use of TBT-SPC paints in anti-fouling systems throughout the 1970s introduced a novel concept with a regulated and steady leaching rate. In other words, when the waves struck the hull, the biocides were discharged. This novel idea led to an approximately 60-month increase in coating life **(Callow, 1990).** Additional benefits of this self-polishing nature include reducing the amount of fuel oil used, preventing the formation of biofouling, and making the hull surface less susceptible to fouling for a longer time because of the unstable substrate **(Clare, 1995).**

4.5 TBT-free copolymer-based technologies /first anti-fouling system free of TBT

Early in the 1990s, the IMO passed the following resolution pleading with governments to forbid paint made of TBT: eliminate the TBT-based paint on non-aluminum vessels less than twenty-five meters. Any paint containing TBT that leaches more than 4 micrograms of TBT per cm^2 per day should be prohibited from use. Due to this resolution, the demand for substitutes becomes critical, leading to the development of several tin-free coatings at the same time as a nonstick coating for small vessels. Nevertheless, research has indicated that using a large amount of copper in antifouling systems can be hazardous to marine life ***(Abbasi et al., 1995*).**

In the 1990s, copper-based paint superseded TBT-based paint. Consequently, approval was given to develop tin-free SPC technologies based on polymers. Two paint types were introduced using silyl acrylate copolymers and high-performance metal copolymers. Copper and zinc were the main metals used in the creation of metal acrylate copolymer paint by the Nippon Paint Company (NPC). The paint was then extensively marketed by NPC and other foreign paint manufacturers, which led the IMO to restrict TBT-based paint ***(Ohsugi, et al., 1989).*** Later, other painting companies like Chugoku Marine Paints (CMP) and Kansai Paint developed related acrylate copolymer paint, which was eventually used commercially ***(Yebra et al., 2004).***

5. Review of the national, international agreements and treats governing the antifouling system.

Table 1: Review of the national, international agreements and treats governing the antifouling system

Country/Organization	Date	Action
France	1982	The inaugural French prohibition on TBT-based paint for boats under 25 meters Control the retail selling of antifouling paint in the west coast of France
UK	1986	Control the retail distribution of antifouling paint.
Sweden, Belgium, Denmark, France, Netherlands, UK, Germany, Norway and Japan	1988	jointly submitted proposal to IMO to forbid the international use of TBT in antifouling methods.
USA	1988	The Organotin antifouling paint management plan signed by the federal
Japan	1990	A complete prohibition on the application of TBT paint
UNCED	1992	It was decided at the Rio Summit to urge the IMO to adopt legislation banning the use of hazardous components in antifouling systems.

Sweden	2002	On Sweden's east coast, smaller ships and recreational boats are not permitted to use copper in anti-fouling solutions.
Denmark	2003	Denmark banned the use of copper, following Sweden's initiative.
EU	2003	All organotin substances are prohibited from being used in antifouling paints by EU regulation (EC No782/2003).
IMO	2008	AFS Convention: 1. It was forbidden for ships to have any organotin substance on their hulls or 2. To stop the TBT from leaking, ships can cover the undesirable paint with other substances.

(SOURCE: DEKINESH, 2018)

6. Methodology

First, a thorough analysis of the available literature was done for the research on the legal concerns, the creation and process of biofouling, and antifouling technologies, such as hull coatings. Furthermore, information has been gathered via surveys sent to large and medium-sized paint producers including Chugoku Paint and Sigma Paint (PPG). Second, a SWOT analysis was performed to gain a better understanding of the advantages, disadvantages, opportunities, and threats related to the information gathered on anti-fouling systems and hull cleaning mechanisms through literature review and questionnaire responses. In this study, a qualitative data analysis was used to code the data into several groups.

7. Data analysis, findings and discussion

Qualitative analysis has been adopted through a SWOT analysis to evaluate the anti-fouling systems that are currently in use. The author classified the gathered data into the following categories:
1. Paint with biocidal agents: anti-fouling based on biocide; paints with soluble matrix; paints that leach; ablative paints; self-polishing copolymer paints.
2. Non-toxic coatings: fouling release coatings; inhibition surfaces; biological mimicry coating; hull bug (brushing tool); cleaning gear (boat washer).

Table 2: SWOT analysis

Anti-fouling category	Strengths	Weaknesses	Opportunities	Threats
biocide dependent anti-fouling	Effective anti-fouling agents	Has environmental impact as biocide based	Based on Copper compound therefore is less hazard than TBT	Regulation for limiting the use of biocides
Paints with soluble matrix	Mixed with matrix/binder/resin	-Leaching overtime -Valid for 18-24 months	Produced from natural wood	Regulation for limiting the use of

			rosin	biocides
Paints that leach	-Insoluble matrix - Hard racing - Low cost	- biocide release - effective time not exceeding 18 months - Negative environmental impact- Creating hazard health- Releases very much quantity of biocides during hull cleaning	Minor hazard biocides	-Regulation for limiting the use of biocides -Significant improvement in other biocides release systems like (CDP, SPC) -New solution evolved not biocides dependent
Ablative paint Or (CDP)	-Soluble matrix/control depletion polymer- affordable- Currently in use	-Dissolution and hydration mechanisms- Contain strong biocides than SPC- Negative environmental impact - Releases biocides during hull cleaning- The leaching mechanism led to hull roughness - Get oxidized when contact with air	-Valid for 36 months-the cost factor dominating the anti-fouling selection	-Regulation for limiting the use of biocides -New solution evolved not biocides dependent
Self-polishing copolymer paint (SPC)	-Copolymer paint matrix and biocides- Copolymer layer compatible with various ship speed -Release rate effectively controlled- Applied widely nowadays- Has five years lifetime	-Negative environmental impact -Costly -Releases biocides during hull cleaning	-Very effective when fuel oil price increases and or, shortage -Advanced mechanism drive to improved smoothness, reduced drag and resistance force, hence less fuel consumption -Depends on new biocides rather than conventional ones	-Regulation for limiting the use of biocides -New solution evolved not biocides dependent
Hybrid (SPC +CDP)	-Release rate effectively controlled -Affordable but more costly than CDP	-Negative environmental impact -Releases biocides during hull cleaning	-Suitable for medium biofouling quantity -Depends on new biocides rather than conventional ones	-Regulation for limiting the use of biocides -New solution evolved not biocides dependent
Fouling release coatings (FRCs)	-Not biocides dependent- Environmentally friendly	-Act only when ship is underway -Soft and vulnerable -Suitable for high-speed ships	-Trigger for researcher to discover new environmentally	-Un avoided Biofilm formation -Non- effective when the ship is

	-Valid for long time	-Ship should be completely out of water during painting -Costly -less efficiency than SPC -Require experienced and professional workers	mechanism -Became an effective solution rather than biocides	stationary -Compete with other Environmentally friendly mechanism
Inhibition surfaces	-Using chemical and physical methods -Environmentally friendly		-Paving the way to use electric conductive coating -Incentives the researchers to delve deeper into more natural products	
Biological mimicry coating	-Natural solution -Simulate the ocean's creatures skin -Environmentally friendly -Prevent the biofilm formation	-Not maturate yet -Tested only at small scale surfaces	-Increasingly pressure by IMO to find the environmentally friendly coating	-Unknown cost -For commercial application, more study is required.
Ultra Sonic Transducer	-No sign of biocides content -Environmentally friendly	-Under water noise -Applied only on small private boat	-Increasingly pressure by IMO to find the environmentally friendly coating	Under water noise regulation
Brushing tool (Cleaning device)	-Both In water/out water cleaning -Require a short time for cleaning - No risk of damage to the coating layer -Enable cleaning micro-biofilm layer -Curb the formation of Macro-biofilm for a long time -Controlling ship's drag and fuel consumption	-Off hire time for cleaning process -Over cost -In case of the release of the active substance during cleaning, the antifouling system will be ineffective - Is not an alternative to the antifouling system -Suitable for cleaning micro-biofilm rather than macro-biofilm	-Regular cleaning to maintain effective ani-fouling system -Use of Nylon brush for sensitive Coating -Support regulation on biocides limitation -Widespread of application	-Source of marine pollution due to cleaning residual -IMO regulation for controlling the biological pollution

8. Findings

The table above shows two main mechanisms for preventing biofouling: the fouling release mechanism and the antifouling mechanism. What differentiates them, and do they succeed in accomplishing the desires of the future, both environmentally and economically?

Initially, in contrast of the antifouling method which implements heavy metals; biocides, as active chemicals to eliminate organisms, the fouling release method, a more environmental friendly technique, relies on the non-stick mechanism and does not release any heavy metals or biocides.

Both mechanisms reduce the fouling thickness rather than completely removing the biofouling on the ship's hull; in other words, they must be integrated with the hull cleaning operation. To address the second question, not only do biocides use chemicals that harm the marine environment, but they also frequently leak, as well as the fouling release method which is vulnerable and performs inadequately in the idle ship and slow steaming modes. Thus, it is evident that both mechanisms have a myriad of disadvantages. Additionally, it is anticipated that new regulations will limit the use of biocides as outlined by the AFS Convention (more precisely, annex 1), hence hindering the advancement of antifouling performances. However, due to the inefficiency of FRC mechanisms, especially when the ship is steaming slowly or lying at anchor, the usage of antifouling mechanisms (biocides-SPCs) will be extended for a longer time, as indicated by a PPG paint company **(Dekinesh, 2018).**

Based on the SWOT analysis, it is noted that the presently applied methods and solutions of anti-fouling systems do not meet the requirements for high performance and environmental impact, therefore it will drive the paint producers to discover new antifouling technology, both environment-friendly and with high efficacy.

9. CONCLUSION

The study's findings demonstrate the vital roles of an antifouling system in terms of environmental impact and economic benefit. Following analysis, the findings reveal that:

(1) Shipping companies are facing difficulties identifying which anti-fouling solution is most appropriate for their fleet to maximize their financial gains.
(2) It is essential to have a decision-making framework that helps shipping companies choose the best antifouling solution to maximize energy efficiency.
(3) There are numerous key factors guiding the shipping companies while selecting the anti-fouling systems such as the type, size of the ship and seagoing areas.
(4) The Shipping companies must adopt and carry out an anti-fouling management strategy.
(5) The requirement for new technology development to achieve a balance between economic interests and impact on the environment.
(6) The need for developing a model to determine and quantify how much fuel oil is consumed as a result of biofouling.
(7) Future anti-fouling technologies could improve ship energy efficiency and contribute to decrease biofouling.

Before the International Maritime Organization (IMO), several countries and organizations prohibited the use of anti-fouling systems based on organotin compounds, which raised concerns about competitive advantage. To prevent the use of organotin chemicals in fouling systems worldwide, these states: Sweden, Belgium, Denmark, France, Netherlands, UK, Germany, Norway, and Japan have submitted a joint proposal to the International Maritime Organization (IMO).The IMO and its member states worked to bring the AFS Convention into effect by the implementation, technical collaboration, survey and certification, and Port state control inspection (enforcement).

10. Recommendations

(1) Provide a comprehensive reference on antifouling systems that are currently in use for shipping companies, this will help decision-makers choose the best system for their fleet.
(2) Addressing the need for new anti-fouling technology to meet the future demand.
(3) Develop a strategy to fill the gap between the current anti-fouling systems and the requirements for new technologies to develop a new anti-fouling system.
(4) The large paint producers' research and development departments should search for new/innovative technology.
(5) Create a model that uses historical data from tankers, containers, and RoPax ships to calculate the possible power savings when examining a new anti-fouling solution.
(6) Design a framework for making decisions while choosing the best anti-fouling technique to maximize energy efficiency.
(7) Shipping companies are required to adopt cost and benefit analysis for selecting the optimum anti-fouling system, compatible with the ship's profile.

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