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Review Paper

Strategic actions for sustainable vessel hull coatings in line with the UN SDGs

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Abstract: Since the adoption of the 17 Sustainable Development Goals (SDGs) by the United Nations (UN) in 2015 for global sustainable development by 2030, the International Maritime Organization (IMO) has also actively worked in line with all SDGs, which should be effectively integrated with a primary central focus on SDG 14 "Life Below Water." This study identifies different views from each stakeholder regarding vessel hull coatings, based on the latest regulatory situation in line with the relevant SDG 3 "Good Health and Well-being" to review the potential human health hazard from biocides, SDG 13 "Climate Action" to revisit the urgent decarbonization action with vessel hull coatings and hull cleaning, and SDG 14 "Life Below Water" to reiterate the potential impact of biocides on the marine environment and ecosystem. The analysis results also highlight the importance of integrating these three SDGs with the enhanced high performing non-toxic vessel hull coatings via proper in-water hull cleaning methods. Key strategic actions are then more specifically recommended in terms of harmonizing and optimizing all three SDGs.

Keywords: Sustainable Development Goals, Non-toxic vessel hull coatings, Antifouling, Biocides, In-water cleaning, Biofoulings

1. Introduction

"Vessel hull coatings" can be applied to the bottom (underwater hull) of ships to prevent biofoulings. According to the explanation by the International Maritime Organization (IMO), "biofouling is the undesirable accumulation of various aquatic organisms (microorganisms, plants, algae and animals) on a submerged structure, such as the underwater hull of ships **[1]**." The widely commercialized vessel hull coating is an "antifouling" paint, which is a mixture of heavy metals and biocides designed to kill marine organisms that grow on ship hulls. Slime, weeds, and marine life, such as barnacles and mussels, start to grow on hulls very quickly when ships are stationary. Consequently, they increase the water resistance, reduce vessel speed, and increase fuel consumption, which also implies more CO_2 emissions. Shipowners usually want the most effective "antifouling" available. Accordingly, marine coating companies apply the most potent biocides permissible by the law.

Regarding the toxicity level of biocides, interestingly, we can easily find this information on material safety data sheets (MSDS) of manufacturers' products, which clearly states that "This material is very toxic to aquatic life with long lasting effects," which means that "it may cause long-term adverse effects in the aquatic environment" **[2]**.

Any type of "antifouling" product is designed to wear away in several mechanisms, such that fresh biocides are always brought to the surface of the coating. As "Antifouling" chemicals (called biocides) and heavy metals enter seawater in the ocean, they gradually sink and accumulate in the seabed. Consequently, their poisons impact marine organisms and re-enter the food chain of humans. However, for a few reasons, the underwater cleaning of vessels to remove various foulings is allowed. When various foulings are cleaned, "antifouling" coating is also removed together with foulings, which also releases a large amount of biocides into the water. Generally, approximately 40%–50% of "antifouling" products consist of toxic copper oxides, biocides, and boosters.

In line with IMO's the Anti-Fouling Systems (AFS) Convention, "the use of harmful organotins in antifouling paints has been prohibited to prevent the potential future use of other harmful substances in antifouling systems" **[3]**. However, several marine scientists and ecologists believe that current replacements of tributyltin (TBT), which was completely banned in 2008, are only slightly less harmful. Accordingly, alternative technologies are currently being used to replace TBT-based products. However, because the "antifouling" performance of these technologies cannot practically measure up to that of TBTs, most coating companies use more copper oxides and boost biocides, which

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threaten the marine environment. Therefore, this issue should be addressed as a priority under proper global governance, and could be driven by the IMO as an initiative for driving and executing the relevant Sustainable Development Goals (SDGs) of the United Nations (UN).

However, regardless of its significance in the marine environment, the initiative of emphasizing the importance of biofouling impact has been addressed as a relatively lesser priority than other ocean environmental issues. First, this study focuses on the situation analysis of major issues and topics related to antifouling products in line with the UN SDGs. These topics are:

- Environmental impacts of “antifouling” paints
- Non-toxic vessel hull coatings: availability and properties
- Regulation of “antifouling” paints: current and future (incl. TBT ban background)
- Economic importance of “antifouling”
- Review of UN SDGs for vessel hull coatings

Second, based on the situation analysis, this study identifies the different views held by each stakeholder, based on the understanding of how interactive they are. Finally, this study offers the strategic actions required for sustainable vessel hull coatings in line with a combination of SDGs 3, 13, and 14.

2. Situation Analysis

2.1 Environmental Impacts of Antifouling Paints

A range of antifouling paints have mainly used toxic materials (called biocides) as the critical content for preventing foulings, which have toxic effects on marine environments. Several studies have identified that antifouling biocides pose a potential environmental risk; for example, owing to the elevated concentration in sediments. In addition, these studies have also emphasized the importance of biological impacts caused by the secondary spread of invasive species into the marine environment **[4]**. These issues cause changes in the marine food web, thereby resulting in altered productivity patterns that impact ecosystems and human health **[5]**.

2.1.1 Toxic chemicals/biocides release to Ocean

Throughout history, various biocides with toxic effects have been employed to kill or deter attached microorganisms **[6]**. Owing to the strict prohibition of TBT antifouling by IMO’s “AFS Convention” in 2008, various alternative (TBT free) paints with other biocides have been introduced at the marine market **[7]**. The majority of current biocide-containing antifouling products have copper oxide and various booster biocides. Before the TBT ban, while these biocides only consisted 20% of each antifouling product; currently, approximately 40%–50% of antifouling is required to mitigate the reduced antifouling performance compared with TBT-based products.

First, when the IMO discussed the ban on the use of TBT in antifouling systems, one of their official responses was that the hazards caused by copper (oxide) are thousands of times less than those by TBT, regardless of some arguments that the alternative products containing copper will trigger the same negative impact as TBT-based antifouling products **[7]**. However, copper has been argued to be a potentially harmful biocide. This needs to be continuously investigated from various perspectives. The use of copper as a biocide in antifouling paints could be a potential environmental problem. In particular, high concentrations of copper, commonly found in shallow and coastal areas, are toxic to organisms. Therefore, efforts to develop environmentally friendly antifouling products that provide sufficient antifouling performance without (or with the lowest amounts of) copper are ultimately required **[8]**.

Second, there are several key booster biocides currently used for antifouling products. The purpose of “booster biocide” is to improve antifouling properties, as the main biocide is usually not sufficient, depending on the fouling type. “Booster biocides” have been tolerated in terms of environmental hazards; however, their antifouling effects could be understood as simply being “boosters” for supporting the main biocide functionality in antifouling products. Typical antifouling paints contain 35–50 wt.% of copper (oxide) as the main biocide, and less than 10 wt.% of “booster” biocides **[9]**.

The most common biocides (copper oxide and booster biocides) are presented in **Table 8**. The fact that the alternatives of TBT are also toxic has raised the ultimate challenge and interest among researchers to conduct further studies on the impact of these alternatives on the marine environment **[6]**.

2.1.2. Invasive aquatic species (IAS) transfer

According to IMO Resolution Marine Environment Protection Committee (MEPC).207(62) Guidelines for the control and management of ships’ biofouling to minimize the transfer of invasive aquatic species, “Invasive aquatic species (IAS) are species that may pose threats to human, animal and plant life, economic and cultural activities, and the aquatic environment” **[1]**. For example,

Table 1: General properties of alternative vessel hull coatings

Item	Copper-based antifouling paint	Epoxy-based and polysiloxane-based vessel hull coating	Silicone-based (incl. fluoropolymers) vessel hull coating
General description	Copper oxides are leached to act as preventative biocide	Hard, durable coating; contain no biocide	Smooth, slick surface; contain no biocide
Durability	To be reapplied at every dry-docking	Lasts longer than copper-based antifouling paints as no polishing or depletion	Lasts longer than copper-based antifouling paints as no polishing or depletion
Maintenance properties	To be stripped by the same antifouling system at every dry-docking	To be cleaned frequently to scrub off attached organisms	To be cleaned if required
Other properties		More resistant to damage than other vessel hull coating types	Vessel speed could be increased if it performs well, and less resistant to damage than other vessel hull coating types

Source: [11][13] and author

the UK P&I Club claims that "the introduction of IAS associated with global shipping has been identified as a significant threat to the world's ocean and coastal ecosystems. Several researchers have suggested that 70%–80% of IAS introductions occur via biofouling" **[10]**.

The spread of invasive species has been recognized as a marine environmental threat, because invasive species might trigger direct and indirect effects on the host environment in competition with native species. According to the possible impact described by IMO "industries that depend on the coastal and marine environment, such as tourism, aquaculture, and fisheries, are exposed to significant adverse economic impacts, as well as costly damage to infrastructure" **[1]**. Therefore, if the prevention of biofouling using antifouling products fails, marine organisms adhering to the underwater surface of vessels can be transferred accordingly.

2.2 Non-toxic Vessel Hull Coatings: Availability and Properties

Owing to the potential pollution challenge of copper (oxide), there have been continuous discussions for revised (or new) regulations to reduce copper levels or a complete ban. To support this review and consideration, several alternative technological solutions have been developed in recent years. Non-toxic hull coatings are therefore readily and commercially available today; however, they have not been widely adopted, mainly owing to efforts, such as full blast, to build up the new coating system with some skepticisms regarding long-term performance **[12]**, as well as their higher application and material prices than biocide-containing "antifouling" products.

There are generally three types of nontoxic hull coatings: silicone-based, epoxy-based, water-based, and polymer-based coatings. Although the proportion of non-toxic hull coatings remains smaller than biocides containing "'antifouling," silicone-based hull and epoxy hull coatings are already commercialized.

As presented in **Table 1**, regarding epoxy-based and silicone-based non-toxic vessel hull coatings, the major reasons why shipowners and ship operators are reluctant to apply these non-toxic vessel hull coatings are primarily related to the high cost (in both material and application costs) and low fouling control performance of silicone-based and epoxy-based hull coatings, respectively.

Epoxy-based, polysiloxane-based, and silicone-based vessel hull coatings are usually called "foul-release" coatings and/or "non-toxic" coatings, which are regarded as environmentally friendly antifouling technologies. These technologies have the physical properties of low surface energy and low elastic modulus to achieve antifouling, and they do not dissolve or decompose in seawater. However, existing technology-related issues, such as the mechanical properties and antifouling performance under static conditions, are believed to be the key breakthrough directions for future research **[13]**.

2.3 Regulation for Antifouling: Current and Future

The most distinctive global regulation for antifouling paints is the TBT ban of the "AFS Convention" by the IMO MEPC in 2001. Antifouling paints, using TBT as a biocide, were developed in the early 1960s, and have been widely used globally until 2008, the year the IMO "AFS Convention' resolution was put into effect.

In the 1980s, several researchers started to emphasize the harmful impact of TBT as a severe toxic substance impacting the marine environment. However, only local prohibitions and regulations were established for small coastal vessels, rather than commercial vessels operating in deep-sea water globally.

In the 1990s, the IMO MEPC continued to study the environmental issues of antifouling paints. In 1990, IMO adopted "an Assembly resolution that called on the MEPC to develop an instrument, legally binding throughout the world, to address the harmful effects of antifouling systems used on ships" **[3]**.

Table 2: Antifouling major regulation events in IMO

Year	Major events	Remark
1989	The harmful environmental effects of TBT compounds were recognized by IMO	Toxic
1990	IMO MEPC adopted a resolution which recommended that governments adopt measures to eliminate the use of antifouling paints containing TBT on non-aluminum hulled vessels of less than 25 m.	Toxic
1999	IMO adopted an Assembly resolution that called on the MEPC to develop an instrument, legally binding throughout the world, to address the harmful effects of antifouling systems used on ships.	Toxic
2001	IMO adopts "AFS Convention" to eliminate TBT from antifouling coatings from vessels through: • 2003 – prohibition of further application of TBT • 2008 – prohibition of active TBT presence	Toxic
2008	IMO "AFS Convention" entered-into-force	Toxic
2011	IMO adopted a Resolution MEPC.207(62) outlining the Guidelines for the Control and Management of Ships' Biofouling to Minimize the Transfer of Invasive Aquatic Species.	IAS
2021	IMO amended the IMO "AFS Convention" to include controls on the biocide "cybutryne." • 2023 – prohibition of antifouling systems containing cybutryne	Toxic

Source: [3] and **[28]**

In November 2001, IMO adopted a new International Convention on the Control of Harmful Antifouling Systems on Ships (called "AFS Convention"), prohibiting the use of harmful organotin compounds in antifouling paints used on ships and establishing a mechanism to prevent the potential future use of other harmful substances in antifouling systems **[3]**. The "AFS Convention" established a global ban on the application of TBT-based antifouling on all vessels after January 1, 2003, including a prohibition of active TBT presence in the paint system after January 2008.

In June 2021, IMO MEPC amended the IMO "AFS Convention" to include controls on the biocide cybutryne (also known under its industry name as Irgarol-1051), which cannot be applied to ships from January 2023 **[14]**.

When IMO discussed the ban on the use of TBT in antifouling systems, their position was that copper (oxide) is far less harmful than TBT **[7]**. However, because these previous studies were conducted 20 years ago, they need to be reinvestigated with more advanced technologies and insights by new experts.

Considering the background and history, new regulations to ban the use of copper and other biocides in antifouling products should be revisited and developed, which might require a similar process to the TBT ban. Meanwhile, shipowners, naval architects, governments, and port authorities, who can make decisions on antifouling types, should bear sustainable responsibilities for the present and future.

2.4 Economic Importance of Antifouling

According to IMO, "antifouling paints are used to coat the bottoms of ships to prevent sea-life organisms, such as algae and molluscs, from attaching themselves to the hull, which slows down the ship and increases fuel consumption" **[3]**.

From the perspective of shipowners and operators, antifouling is economically very important, as it might be critically influenced by operational efficiency of fuel consumption of vessels, as presented in **Table 3**.

According to the results of the Global Maritime Energy Efficiency Partnership (GloMeep) project driven by IMO, "the coatings will reduce the resistance of the ship hull through water, including the required engine power, thereby reducing fuel consumption." **[15]**.

Table 3: Fuel consumption reduction by vessel hull coatings

Item	GloMeep Project output
Cost of hull coating	USD30,000 to USD500,000 depending on the vessel size
Fuel consumption reduction potential	Up to 8% of overall ship's frictional resistance, allowing 1% to 4% reduction on main engine fuel consumption

Source: [15]

This is the area that we should investigate to develop measures to minimize the gap and optimize the solution between economic importance and environmental impact, which could be objectively reviewed from a sustainable perspective.

2.5 The UN SDGs Review for Vessel Hull Coatings

According to the UN website, "the SDGs were adopted by all UN member states in 2015 as a universal call to action to end poverty, i.e., to protect the planet and ensure that all people enjoy peace and prosperity by 2030". It has a total of 17 goals (with 169 sub-targets), which are closely integrated with each other because any action or outcome from one might affect actions or outcomes in other goals, which should be balanced and harmonized in terms of social, economic, and environment sustainability **[16]**.

As a specialized agency in the UN, the IMO also has a serious responsibility to support the UN SDGs in terms of the safety and security of shipping, as well as the prevention of marine pollution from vessels, given their main commitments "to create a regulatory framework for the shipping industry that is fair and effective, universally adopted and implemented" **[17]**.

This study emphasizes the importance of vessel hull coatings in achieving key topics of the SDGs, which are summarized in **Table 4**.

Table 4: UN SDGs in conjunction with vessel hull coatings

SDGs	Description
SDG 3 - Good Health and Well-being	Ensure healthy lives and promote well-being for all at all ages
SDG 13 - Climate Action	Take urgent action to combat climate changes and its impacts
SDG 14 - Life Below Water	Conserve and sustainably use the oceans, seas and marine resources for sustainable development
SDG 17 - Partnerships for the Goals	Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development

Source: [18]

SDG 14 – Life Below Water

Among these SDGs related to vessel hull coatings, SDG 14 has a more direct impact on the marine industry. Therefore, IMO has a centralized role for SDG 14, while all SDGs are closely linked to each other.

According to the study by IMO (2017), "the main pollutants of concern with respect to shipping are oil, hazardous and noxious substances and other cargoes capable of causing harm, sewage, garbage, air pollutants, antifouling agents for hull treatment, and transported invasive species." Based on IMO's regulatory guidelines, such as its international conventions and codes, these matters have frequently been issued by the global community **[19]**. The IMO's global regulatory conventions or resolutions regulate a range of pollution caused by vessels.

Therefore, SDG 14 targets should be reviewed from the IMO perspective to identify tangible actions related to antifouling and biofouling regulations. In June 2018, an IMO regional workshop was held to address the impact of biofouling by ships at Trinidad and Tobago, a port in Spain. According to a recent news article that explains IMO activities, "the workshop, attended by 45 participants from 13 countries, was held based on IMO's technical cooperation fund." The main agenda of this workshop was centered on how to support the UN SDG 14 target based on the IMO's existing and future regulations and guidelines **[20]**. However, there has been no specific discussion regarding the antifouling or biofouling issue in terms of the UN SDG 14.

Sub-targets 14.1 and 14.2 for achieving SDG 14 could be specifically reviewed in relation to the issue of the release of antifouling toxic chemicals and biocides to the ocean (including drydocking and cleaning works as land-based activities). Sub-target 14.2 is also closely related to the transfer of invasive aquatic species by vessels via biofouling.

Table 5: SDG 14 sub-targets relating biocides into the ocean

14.1	"By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution"
14.2	"By 2020, sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience, and take action for their restoration in order to achieve healthy and productive oceans"

Source: [18]

In line with sub-targets 14.1 and 14.2 of SDGs, IMO has two regulations directly related to antifouling and biofouling, including invasive aquatic species, as comparably presented in **Table 6**.

Table 6: IMO regulations for biofouling, antifouling and invasive species

Biofouling / antifouling related	IAS related	Mandatory	SDG sub-targets
AFS Convention - "International Convention on the Control of Harmful Antifouling Systems on Ships"			
YES	-	YES	14.1 and 14.2
Biofouling Management - "Resolution MEPC.207(62) - The Guidelines for the Control and Management of Ships' Biofouling"			
YES	YES	-	14.2

Source: Author

The "AFS Convention" regulation is mandatory while "Biofouling Management" is based on Resolutions (not mandatory), rather than the Convention regime.

In June 2021, the 76th MEPC decided to ban "cybutyne," which had been used as a biocide in antifouling paints for a long time. However, given the fact that 'cybutryne' has been used by only limited coating companies, this adoption is not enough to pursue the ultimate purpose of SDG 14.

SDG 14 has ten sub-targets that are insufficient with no direct indicators to verify and reduce the negative environmental impact of biocides from antifouling into the ocean. As stated in Resolution MEPC.207(62), although the potential impact of biocides released at the time of hull cleaning is clear, the SDG sub-target 14.2 has already exceeded the target period of 2020 without specific new indicators to prohibit or limit biocides and biofouling management.

SDG 3 – Good Health and Well-being

Given that a lot of foods that humans consume are produced from the oceans, the potential impact of biocides from antifouling products on human health should be considered as a critical subject in terms of SDG 3. More specifically, sub-target 3.9 of SDG 3 also emphasizes the potential health risk from hazardous chemicals.

Table 7: SDG 3 sub-target relating biocides into the ocean

3.9	"By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollutions and contamination"

Source: [18]

"substances" must be re-approved before the expiration of the grace period by the end of December 2029. Meanwhile, a grace period of two additional years is given to biocidal "products" that use these active substances, thereby extending the expiration date to the end of December 2031.

Interestingly, the regulatory restriction for these biocides by K-REACH is now more aggressive than K-BPR in terms of timing (see **Table 8**). Given the public notification of the toxicity level threshold recently stipulated for some active ingredients (selektope and DCOIT), further guidelines on other active ingredients (CPT, ZPT, and copper oxide) will be supposedly announced after a thorough investigation in due course. This means that all major biocides in antifouling products are likely to be re-classified as toxic substances with the clear limitation of mixture weight percentages, which are generally lower than the current ones in their formulations.

Table 8: Antifouling products' major biocides status in K-REACH and K-BPR

Biocides	CAS No.	Chemical Name of Active Substances	K-REACH		K-BPR	
			Threshold in mixture (weight%)	Public notification	Item No	Grace period for existing active substance
Econea	122454-29-9	4-Bromo-2-(4-chlorophenyl)-5-(trifluoromethyl)-1H-pyrrole-3-carbonitrile	25.0%	2008	499	31 Dec 2029
Selektope	86347-14-0	5-[1-(2,3-Dimethylphenyl)ethyl]-1H-imidazole	1.0%	2011	474	31 Dec 2029
DCOIT	64359-81-5	4,5-Dichloro-2-N-octyl-4-isothiazolin-3-one	1.0%	2017	419	31 Dec 2029
CPT	14915-37-8	2-Pyridinethiol-1-oxide, copper salt	Under investigation (See Note 1)		329	31 Dec 2029
ZPT	13463-41-7	Zinc pyrithione			317	31 Dec 2029
Copper oxide	1317-38-0	Copper monoxide			160	31 Dec 2029
	1317-39-1	Dicopper oxide			161	31 Dec 2029
Zineb	12122-67-7	Zineb	Possibly in 2025 (See Note 2)		311	31 Dec 2029

Source: [21], **[22]** and the author

Note 1: Under the investigation by MoE (The Minister of the Environment) based on the hazardous test results by NIER (The National Institute of Environmental Research) – The threshold cut-off is likely to be 1.0%.

Note 2: Zineb will be dealt with as the different scope (100 - 1,000 ton/year is the highest tonnage level) to be registered in K-REACH, which is likely to be clarified by 31 December 2024.

In line with SDG 3, several countries have already tightened regulations on chemicals such as REACH (Registration, Evaluation, Authorization of Chemicals), and are also tightening regulations on biocide substances used in various industries, via a separate regulation called BPR (Biocidal Product Regulation). South Korea also has the same regulation purposes, which are called K-REACH and K-BPR.

According to K-BPR, "any person who intends to manufacture or import active substance for use in biocidal products must prepare and submit the appropriate data and obtain approval from the Minister of the Environment. The validity of active substance approval is within 10 years in case of biocides for Antifouling products" **[21]**.

Among the 594 biocides listed by K-BPR with grace periods (3–10 years) to obtain approval from the Minister of the Environment, a total of 33 biocides are currently categorized by the use of antifouling products. The required approval dates for the 33 biocides used in vessel hull coatings have been suspended with a grace period of 10 years, which means that these active

Regardless of K-REACH or K-BPR, an ultimate ban or strict restriction on biocides would be obvious in the future with just a matter of time. Therefore, more proactive responses from producers, users, and government bodies are required. As previously emphasized in Chapter 2-2, non-toxic vessel hull coatings are already commercialized in the market, where more an active institutional support for the development of high-performing non-toxic vessel hull coatings is required by the government.

SDG 13 – Climate Action

Seeing the description of SDG 13 "Take urgent action to combat climate changes and its impacts," SDG 13 is currently considered as a priority among all SDGs. However, because international shipping vessels do not operate within the territory of a particular country, it has been difficult to manage carbon

Table 9: IMO decarbonization regulation status

Entry into force	New Vessel Energy Efficiency	Fuel Consumption Report	Existing Vessel Energy Efficiency	Market Based Measure
2013			SEEMP and EEOI	
2015	EEDI – Phase 1 (10% reduction)			
2019		Data Collection System		
2020	EEDI – Phase 2 (20% reduction)			
2023			EEXI and CII	
2025~	EEDI – Phase 3 (30% reduction)			Carbon Tax or Credit Trading

Source: Summary of the key properties and effective timings of IMO decarbonization regulations
Note: SEEMP – ship energy efficiency management plan, EEOI – energy efficiency operational indicator

emissions per country, although other industries have exhibited the proactive implementation of decarbonization policies and drives for each country. As a specialized agency in the UN, the IMO has made efforts to take this priority, resulting in remarkable regulations that are now closely aligned with the UN SDG 13 "Climate Action."

In 2018, the IMO adopted an initial strategy to reduce greenhouse gas (GHG) emissions from ships. Levels of ambition include a CO_2 emission reduction of at least 40% by 2030, compared to 2008, and a total GHG emission reduction from shipping by at least 50% in 2050, compared to 2008 **[23]**.

The IMO's regulatory movement for decarbonization is summarized in **Table 9**. In general, the target vessel for decarbonization is being expanded from newbuild vessels to existing vessels, and the reduction method is also expanding from the design and technical aspects of the vessel (in EEDI- energy efficiency design index) to operational aspects (in EEXI- energy efficiency existing ship index, and in CII- carbon intensity indicator), and is now pushing for market-based measures (MBM) from an economic perspective.

In conjunction with the subject of this study, the vessel hull coating has important direct and indirect impacts on these regulations, because it is very closely related to the vessel fuel efficiency (1%–4% reduction in main engine fuel consumption) **[15]**, according to the GloMEEP, which was launched in 2015 by the IMO.

More specifically, for each regulation, although the vessel hull coating element was not directly reflected in the EEDI formula implemented in 2015 (only indirectly reflected in the event of vessel sea trials in verification), it will have a significant and direct impact on the CII, which will be implemented in 2023.

The attained CII can be calculated as the ratio of the total mass CO_2 (M) emitted to the total transport work (W) **[24]** as follows:

$$attained\ CII_{ship} = M/_W \qquad (1)$$

This simple formula of the attained CII could be paraphrased as expressed in (2) to explain how vessel hull coating can directly impact the attained CII, together with the impact on the vessel fuel consumption, such as the low friction vessel hull coating with less fouling, minimized drag resistance and skin friction, and vessel hull cleaning to remove biofoulings.

$$\text{Attained CII} = \frac{\textbf{Fuel Consumption} \text{ x Conversion Factor}}{\text{Ship's Capacity x Distance travelled}} \qquad (2)$$

Note: Conversion Factor depends on vessel fuel type

Contemporary environmental and regulatory considerations have justified the essential requirement to develop new advanced high-performance products, policies, and procedures that will improve the quality of life, health, safety, the environment **[6]**, and economic benefits.

2.6 Conflict between Stakeholders

Although a biocide-free solution for antifouling products is an attractive target as it is environmentally conscious, this issue is in contrast with a majority of commercially available solutions **[25]**. Regardless of the requirements of new advanced high-performing non-toxic "vessel hull coatings." there have been disagreements among stakeholders (shipowners, coating companies, governance bodies and non-governmental organizations (NGOs)), who should be aligned in terms of sustainability.

<u>End users – shipowners and operators</u>

In November 2001, IMO adopted "a new International Convention on the Control of Harmful Antifouling Systems on Ships (called AFS Convention), which will prohibit the use of harmful organotin compounds in antifouling paints used on ships and will establish a mechanism to prevent the potential future use of other harmful substances in antifouling systems" **[26]**. However, most of them believe that the current non-toxic (non-biocidal) coatings require a higher initial cost than normal "antifouling" products. They are reluctant to apply expensive "non-toxic (non-biocidal)" coatings and prefer to use “toxic (biocidal) antifouling” products.

As shown in **Table 1**, most non-toxic vessel hull coating products “last longer than copper-based antifouling paints” because there is no polishing or depletion mechanism, which means that no full repair is required at every drydocking. Although coating manufacturers claim that non-toxic vessel hull coatings provide the ultimate long-term cost-benefit mainly caused by lowering maintenance and repair costs, several shipowners exhibit a lack of confidence in this area with strong skepticism.

Suppliers - coating companies

Most global coating companies have developed “non-toxic (non-biocidal)” coatings in line with environmental requirements in the future. Some products have been commercially recognized by some shipowners in terms of their fuel efficiency, as well as their green image. However, these coating companies are reluctant to further invest in developing or enhancing this area, because most of their customers, i.e., shipowners, remain reluctant to use non-toxic (non-biocidal) coatings, owing to the high initial cost, and IMO has not seriously and deeply considered banning current toxic (biocidal) antifouling products. A dilemma exists between economic and environmental perspectives among the three dimensions of sustainability.

NGOs / IMO

Several NGOs, together with marine scientists and ecologists, believe that current alternative biocides (instead of TBT) are only slightly less harmful than TBT, which was completely banned in 2008. Some NGOs believe that the current biocidal “antifouling” products should be immediately stopped, given the serious environmental and potential human health problems. They also frequently emphasize this issue as one of the priorities of IMO, with the aim of ending the toxic pollution of “antifouling” products.

Regardless of the NGO’s opinion, the IMO appears not to seriously consider revisiting it or prioritizes it less than other issues such as climate actions, based on their previous position in 2002 that the copper-based (current) biocidal antifouling provides the benefit of less harm to the marine environment after the ban on TBT.

However, this IMO’s old view almost 20 years ago, in relation to biocides currently used in antifouling products, should be revisited in terms of harmful chemicals, biological, and human health hazards with novel technologies and insights, together with various experts and NGOs.

New potential conflict between SDG 13 and 14

The position of each stakeholder on the vessel hull coatings described above is likely to be adjusted as being directly or indirectly impacted by the IMO's new decarbonization regulations, such as EEDI, EEXI, and CII described in Chapter 2-5.

Shipowners should consider all possible factors that can positively impact CII verification annually, which will enter into effect on January 2023. The role of vessel hull coatings could be considered as a potential solution for obtaining better CII levels together with other energy-saving devices. Therefore, although the low-level antifouling products used to be preferred by some shipowners, it is now expected that they will apply higher-performing vessel hull coatings to obtain better CII levels (i.e., more decarbonization in SDG 13 aspect) by maximizing the fuel efficiency of vessels.

The potential concern is that if existing non-toxic vessel hull coatings do not perform sufficiently well with clear cost-benefit for shipowners, between coating investment cost and CII benefits, such administrative incentive and/or preference by their customers, in this case, shipowners are likely to use high-performing toxic (biocidal) antifouling products in SDG 13, rather than shifting to expensive non-toxic vessel hull coatings in SDG 14.

Conversely, although non-toxic vessel hull coatings might contribute to SDG 14 with a negative impact on SDG 13, advanced high-performing non-toxic vessel hull coatings are not developed on time. As explained in Chapter 2-5, K-REACH and K-BPR regulations continue to restrict the use of major biocides. Without better antifouling performance with just no (lower) biocides, although these products can contribute to SDG 14, significant deterioration in SDG 13 could occur in terms of fuel efficiency and decarbonization.

3. Recommendation

Throughout the situation analysis, this study identified that there are four stakeholders who should take strategic actions on “sustainable vessel hull coating.”

- IMO and governments as a governance body
- Shipowners and operators as end-users of vessel hull coatings
- Marine coating companies
- NGOs (scientists/researchers)

From the situation analysis, all four stakeholders have relatively different perspectives in terms of the three dimensions of sustainability: economic, environmental, and social **[18]**, which should be aligned with each other for the ultimate goal of sustainability. Therefore, this study recommends key strategic actions for sustainable vessel hull coatings in line with SDGs 3, 13, and 14 in integrated conjunction with stakeholders who have different preferences or pursuits.

3.1 Enhance Non-Toxic Hull Coatings in SDG 3, 13 and 14

As explained in Chapter 2-2, non-toxic vessel hull coatings, such as silicone-based and epoxy or polysiloxane-based technologies, have been developed and commercialized in the marine coating industry. However, the proportion of non-toxic hull coatings actually being applied in the market remains smaller than that of biocide-containing "antifouling" products.

Table 10: The UN SDGs in conjunction with vessel hull coatings

Company	Product	Type
Chugoku	Bioclene HB Bioclene Plus	Silicone
Hempel	Hempaxil X3+ Hempaguard X5 Hempasil 77300	Silicone
International	Intersleek 1001 Intersleek 1100SR	Silicone Fluoropolymer
Jotun	SeaLion Repulse SeaQuest SeaLion Resilient	No info No info Epoxy-polyxiloxane
PPG	Sigmaglide 890 Sigmaglide 1290	Silicone

Source: coating companies' websites, www.cmp-chugoku.com, www.hempel.com, www.international-marine.com, www.jotun.com, www.ppgmc.com

There are several simple reasons why the market is not yet ready to shift to non-toxic hull coatings instead of current biocidal antifouling products. For non-toxic silicone-based hull coating products, their product features such as high initial cost, application difficulties, and mechanical properties, have been recognized by end-users (shipowners and shipyards) as major barriers in terms of adopting to their vessels in-service and in-building.

This study emphasizes the importance of all stakeholders' efforts. For coating manufactures, they should therefore continue to develop innovative "fuel efficient" hull coatings with non-toxic properties. Although several coating companies have already developed non-toxic vessel hull coating products, as presented in **Table 10**, a few products have been well recognized by shipowners and maintained in the market with actual track records. Most coating companies focus on biocidal toxic antifouling products rather than non-toxic products with less preference by shipowners.

To encourage coating companies to continuously develop further enhanced high performing non-toxic hull coatings, the support of other stakeholders (shipowners, IMO, and governments) is essential.

Regarding shipowners or ship operators as end-users of antifouling products, they should evaluate the current existing non-toxic (non-biocidal) hull coatings in terms of "fuel efficiency," and proactively use these products in line with new decarbonization regulations, such as a CII, which will enter into effect on January 2023. A reason for the reluctant adoption of current non-toxic (non-biocidal) products is related to the high cost of the initial coating in the short term. However, it could eventually be offset if the products provide fuel efficiency in the long term with the benefits of better CII levels, which should be evaluated annually.

Regarding IMO and each nation's government, because SDG 13 "Climate Action" has been addressed as a priority with full attention, SDG 14 "Life Below Water," as well as SDG 3 "Good Health and Well-being" should also be objectively prioritized and reviewed in terms of relevant potential environmental and human health impacts caused by biocides used in current antifouling products. This study provides a simple justification for the need for advanced non-toxic vessel hull coatings.

3.2 Improve Vessel Hull Cleaning Methods in SDG 3, 13 and 14

Experienced shipowners and operations are aware that the issue of vessel hull cleaning is an important action in pursuing "fuel efficiency" in vessel operations. In particular, in-water cleaning of the vessel hull would be an immediate and effective action to obtain a better CII level, which is eventually in conjunction with SDG 13 from the IMO perspective. Owing to this regulatory drive from CII, in-water cleaning of the vessel hull is expected to occur more frequently than now for the annual verification of the new regulation CII.

Therefore, under the new operational situation driven by new regulations for SDG 13, the potential high risk of invasive species transfer from vessel hull cleaning should be investigated in line with SDG 3 and 14 with more attention.

This study identified the human health risk with ecological effects in terms of SDG 3 and 14. According to Adel Ali Desher (2018), "the exotic species can destroy the environment and threaten the health and safety of human populations. In any ecosystem, the introduction and spread of exotic species are highly harmful because of the negative and irreversible changes that can result" **[26]**.

However, the open secret is that illegal in-water hull cleanings on vessels have been frequently occurred in several countries. Given the actual situation when vessels are cleaned at or near ports and coastal areas, it can result in not only creating biofouling debris with invasive species, but also in triggering the unnecessary depletion of antifouling coatings with the premature release of biocides that can harm coastal environments in line with SDG 14.

The vessel hull in-water cleaning could have different levels of environmental risk, depending on the types of cleaning machines or vehicles, types of antifouling products, amounts of biocides released, and biocide residue from biofoulings removed.

The methods of vessel hull in-water cleaning, currently applied to large commercial vessels, are dominated by mechanical scrubbing methods, which adopt motor power to rotate the brush and remove biofoulings. These mechanical cleanings are likely to further increase the release of biocides. The other concern is that only a few cleaning machines have specific reclamation functions, which could be a serious issue in terms of minimizing the transfer of invasive aquatic species.

To minimize the unnecessary biocide release caused by in-water cleaning, contactless cleaning methods (such as high water pressure) are strongly recommended, which are also important for minimizing the mechanical damage on non-toxic silicone paint surfaces. Importantly, to minimize the transfer of invasive species when a vessel underwater hull is cleaned by in-water cleaning, shipowners, ship operators, and coating companies must use cleaning equipment or vehicles with reclamation functions, which is also very beneficial in minimizing the biocide residue on biofoulings removed.

The other issue is the less legal binding of regulations for vessel hull cleanings. Although IMO's resolution "MEPC.207(62)" could be used as a guideline for vessel hull in-water cleaning and maintenance, it has no legal backing and is not mandatory. The right regulation for in-water hull cleaning and its legal bindings would be essential to achieving SDGs 3 and 14, where the IMO's proper attention and efforts are required.

3.3 Cultivate NGOs Role in SDG 17

The purpose of the SDG 17 "Partnerships for the Goals" is to support the achievement of the SDGs and to harmonize and pursue synergy from all individual SDGs throughout the global partnership for sustainable development. The IMO currently has partnership arrangements with more than 70 NGOs, including major global environmental organizations and bodies **[27]**. Regardless of the potential hazards in SDG 3 "Good Health and Well-being" and SDG 14 "Life Below Water," the issue of antifouling products in terms of human health and food chain, owing to "invasive aquatic species" and "biocide" sediment pollution has been relatively less highlighted by current NGOs than other social issues such as SDG 13 "Climate Action."

Because the previous NGOs played a significant role in identifying the TBT's dangers to the environment and human health, which eventually led to the ban on the use of TBT in the international convention 20 years ago, current NGOs will have to benchmark the lesson learned from that period, and they need to propose alternative solutions in conjunction with sustainable, non-toxic, high-performance vessel hull coatings, as well as proper in-water vessel hull cleaning methods.

4. Conclusion

High-performing advanced non-toxic vessel hull coatings can significantly contribute to satisfying SDGs 3, 13, and 14, if each stakeholder, which include shipowners, coating companies, IMO, governments, and NGOs, can be effectively integrated by the ultimate subject "sustainability."

Certainly, for overall and clear consensus, it could require time-consuming efforts to harmonize the preferences and priorities of each stakeholder in their own arenas, where the SDG should play a crucial role with the ultimate purpose of "sustainability."

Therefore, the efforts and leadership of assertive leaders and experts from each stakeholder would be essential to establish the right direction for sustainable vessel hull coatings in the maritime industry. This study provided a fundamental justification and specific agenda for SDGs 3, 13, and 14, requiring more intensive research in terms of regulations, ecosystems, and coating or alternative novel technologies for sustainable vessel hull management.

Author Contributions

Conceptualization, H. J. Kim; Methodology, H. J. Kim; Software, H. J. Kim; Formal Analysis, H. J. Kim; Investigation, H. J. Kim; Resources, H. J. Kim; Data Curation H. J. Kim; Writing-Original Draft Preparation, H. J. Kim; Writing-Review & Editing, H. J. Kim; Visualization, H. J. Kim; Supervision, H. J. Kim;

Project Administration, H. J. Kim; Funding Acquisition, H. J. Kim.

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