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Enhancing Ship Energy Efficiency and Preventing Pollution through Effective Biofouling Control Measures as a Future Direction for a Sustainable Shipping

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ABSTRACT: In recent years, the global emphasis on climate and environmental protection has been increasingly prominent, with the maritime industry playing a critical role in this endeavour. The path to decarbonizing maritime transport is marked by the implementation of stringent regulations such as EEXI/CII and EEDI, aimed at reducing greenhouse gas emissions and enhancing energy efficiency. As industry navigates this transitional phase, there is a growing need for cost-effective solutions that align with evolving environmental standards. One frequently underappreciated factor influencing fuel consumption and total emissions is biofouling—the accumulation of marine organisms on ship hulls. Biofouling significantly increases drag, leading to heightened fuel consumption and emissions, with severe cases potentially increasing emissions by up to 55%. This article explores the impact of biofouling on maritime sustainability, discussing its effects on fuel efficiency, emissions, and environmental pollution, while examining current regulatory frameworks and innovative mitigation strategies such as in-water cleaning and advanced anti-fouling technologies. By addressing biofouling effectively, the maritime sector can make substantial strides towards meeting decarbonization targets and reducing its ecological footprint.

1 INTRODUCTION

The maritime industry serves as a vital economic foundation, as ships transport 90% of global trade. The heavy reliance on shipping operations results in environmental challenges due to energy consumption and pollution [1]. The International Maritime Organization (IMO) emphasizes that shipping must reduce its greenhouse gas (GHG) emissions to achieve at least a 50% reduction from 2008 levels by 2050 (International Maritime Organization, 2018). The shipping industry experiences increased fuel consumption and emissions primarily due to biofouling. Biofouling refers to the unwanted accumulation of microorganisms, plants, algae, and animals on underwater surfaces, particularly ship hulls. Ship hulls affected by biofouling exhibit increased hydrodynamic drag, which leads to elevated fuel consumption and operational costs. Biofouling causes energy inefficiencies and poses ecological risks through the spread of invasive species and the release of toxic substances from antifouling coatings [2]. This paper investigates how biofouling control practices influence ship energy performance and pollution reduction efforts. It describes biofouling mechanisms, current management strategies, and emerging technologies that improve energy efficiency while mitigating environmental impacts. By implementing effective biofouling control strategies, the shipping industry can enhance operational efficiency and contribute to a sustainable maritime future.

2 BIOFOULING

The natural process of biofouling happens when aquatic organisms settle on underwater surfaces especially ship hulls. The maritime industry faces major difficulties because of this phenomenon which damages vessel performance while raising fuel costs and creating risks of invasive species entry into new environments. The growing global shipping industry requires better knowledge of biofouling mechanisms and stages and influencing factors which benefits ship operators and marine biologists and environmental managers.

Biofouling describes the unwanted growth of microorganisms together with plants and animals and algae on underwater surfaces which mostly occur in marine environments [3]. The biofouling organisms include bacteria and diatoms as well as larger species such as barnacles and mussels and seaweeds. The accumulation of organisms on ship hulls modifies its physical structure while simultaneously causing hydrodynamic performance issues which result in drag increase and fuel efficiency reduction.

2.1 *How Biofouling is Created*

The process of biofouling begins with the settlement of microorganisms on submerged surfaces. Several factors contribute to the creation of biofouling, including surface characteristics, environmental conditions, and biological factors.

2.1.1 *Initial Settlement of Microorganisms*

The first stage of biofouling starts when microorganisms begin to attach themselves to ship hulls. The first stage of biofouling starts when a ship enters water and continues to develop after that initial contact. The surface of the hull becomes colonized by bacteria and phytoplankton through physical and chemical interactions during this stage.

Mechanisms of Attachment

- Physical Forces: The surface attachment of microorganisms occurs through three main forces which include van der Waals forces and electrostatic interactions and hydrophobic effects [4]. The forces enable bacteria together with other microorganisms to stick to the hull during their initial contact.
- Chemical Interactions: The chemical composition of the hull surface can influence microbial adhesion. For instance, surfaces with specific chemical groups may promote or inhibit the settlement of certain microorganisms
- Biological Factors: The settlement of particular microorganisms depends on the specific chemical groups which exist on surface materials. Bacteria can produce extracellular polymeric substances (EPS), which create a sticky matrix that enhances adhesion and serves as a substrate for additional organisms.

2.1.2 *Biofilm Development*

The microorganisms establish themselves and multiply to create biofilms which consist of complex microbial communities that use EPS as their structural matrix. The formation of biofilms usually begins within a time span of days to weeks after the initial settlement of microorganisms.

Biofilms contain multiple microbial species which include bacteria together with algae and fungi. The diverse nature of biofilm communities makes them more resistant to environmental stressors. Mature biofilms demonstrate enhanced resistance to antimicrobial agents and physical removal techniques. The resistance of biofilms creates difficulties for cleaning operations and management strategies.

2.1.3 *Macrofouling (Settlement of Larger Organisms)*

The last phase of biofouling leads to the maturation of the fouling community which results in stable species composition and species interactions. The community maturity stage creates intricate ecological relationships because species compete for resources and habitat space. The biofouling community maturation results in increased hull roughness which produces higher hydrodynamic resistance and fuel consumption. The establishment of mature biofouling communities leads to negative impacts on local ecosystems through competition with native species and habitat modification.

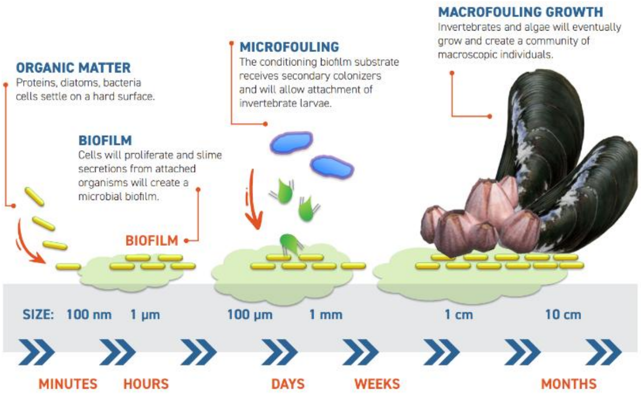

Figure 1. Biofouling process [5]

2.2 *Conditions Impacting Biofouling Creation.*

The speed at which biofouling occurs on ship hulls depends on multiple environmental conditions as well as operational elements. Knowledge of these factors is vital for establishing effective management and mitigation strategies

2.2.1 *Duration of Anchorage*

Duration of anchorage the time a ship spends stationary in one place determines how much biofouling will develop. The length of time ships spend anchored determines the extent of their fouling development since continuous motion reduces fouling development. Extended anchorage time enables microbial films to grow into mature structures which allow bigger organisms to colonize the ship surface.

2.2.2 *Water Temperature*

Fouling organisms depend on water temperature to survive because it controls their metabolic processes and growth patterns. Warmer ocean temperatures speed up microbial growth which leads to faster biofilm development followed by increased macrofouling occurrence. Research findings indicate that biofouling development occurs at twice the speed in warm water conditions as it does in cooler waters [6]. The increasing global temperatures will make this relationship more crucial for biofouling management.

2.2.3 *Salinity Levels*

The amount of salt in water determines both the types of fouling organisms that can live there and how quickly these organisms grow. Different species of fouling organisms show different resistance levels to salt concentrations which determines their ability to settle on ship hulls. Ship barnacles succeed best in brackish waters but other barnacle species thrive better in saltwater environments. The different salinity conditions of operational waters create separate fouling patterns that vessels encounter.

2.2.4 *Nutrient Availability*

The development of biofouling depends heavily on how much nitrogen and phosphorus exists in the water. Water areas with elevated nutrient concentrations support greater phytoplankton populations which serve as food for fouling organisms. The growth of fouling communities becomes restricted when environmental nutrient levels remain low. The prediction of fouling potential requires complete knowledge of how nutrients behave in local water systems.

2.2.5 *Operational Speed*

The rate at which ships move affects how fast biofouling develops. The fast movement of vessels produces water turbulence which disrupts organism attachment to hull surfaces. The prolonged operation of vessels at elevated speeds results in reduced fouling compared to those which operate at lower speeds or remain docked for extended periods. Biofouling management requires understanding of operational patterns as a key factor.

2.2.6 *Water Quality and Pollution*

Pollutants in the water environment together with contaminants create additional challenges for biofouling. Heavy metals along with other toxins create barriers for specific fouling organisms to grow but organic pollutants enhance the development of different fouling species. Biofilms derived from other sources including sewage release create environments which promote fouling development. Biofouling risks become more manageable when water quality receives effective management practices.

2.3 *Impact on Ship Performance*

Biofouling significantly impacts ship performance in several ways.

2.3.1 *Increased Drag and Fuel Consumption*

The rough surface produced by fouling organisms generates drag which results in increased fuel usage. Biofouling causes vessels to consume 20% to 40% more fuel according to Streeter [7] which leads to major economic expenses.

2.3.2 *Reduced Speed and Manoeuvrability*

The presence of fouling organisms creates obstacles that reduce ship speed and manoeuvrability which negatively impacts operational efficiency and schedule reliability.

2.3.3 *Increased Maintenance Costs*

The need for regular cleaning operations to restore operational efficiency results from biofouling presence which increases maintenance expenses. The need for dry-docking operations becomes more frequent because of biofouling which increases maintenance expenses.

2.3.4 *Environmental Pollution*

The process of biofouling enables invasive species to enter new environments which causes damage to local ecosystems and results in biodiversity loss. The use of antifouling coatings results in harmful substance releases that pollute marine environments.

The process of biofouling on ship hulls depends on multiple environmental elements and operational conditions. The development of biofouling requires knowledge about its mechanisms and stages together with environmental conditions for effective management and mitigation strategies. The growing global shipping industry requires immediate solutions to address both economic and ecological consequences of biofouling for sustainable maritime operations. The maritime industry can achieve efficient environmentally responsible operations through advanced technologies and proactive management approaches to minimize biofouling impacts.

3 EEXI AND CII REGULATIONS

The shipping sector's greenhouse gas (GHG) emissions primarily arise from the combustion of fossil fuels. The Fourth IMO GHG Study, conducted in 2020, estimates shipping emissions at approximately 1,076 million tonnes of CO2 equivalent during 2018 [8]. The International Maritime Organization (IMO) has established two major targets: to reduce total annual GHG emissions by at least 50% below 2008 levels by 2050 and to eliminate all GHG emissions by the end of the century. Achieving these targets requires immediate action and the implementation of effective measures.

The shipping industry faces rising demands to reduce its environmental footprint, particularly regarding GHG emissions. The maritime sector generates approximately 2-3% of global GHG emissions, functioning as a major facilitator of global trade. To address these environmental issues, international regulations have been established to promote ship energy efficiency and emission reduction. The Energy Efficiency Existing Ship Index (EEXI) is a crucial regulatory tool designed to improve ship energy efficiency and decrease GHG emissions.

GHG emissions from the shipping sector are directly linked to fuel consumption. The amount of CO2 emissions produced during operations depends on both the type of fuel used and the quantity consumed. According to the IMO, a 1% reduction in fuel consumption results in approximately a 3% reduction in GHG emissions [8] Thus, achieving GHG reduction targets depends on optimizing operations and managing fuel consumption to enhance energy efficiency.

3.1 *EEXI*

The EEXI represents a regulatory framework which the IMO created to boost the energy efficiency of ships already in operation. The EEXI entered into effect in 2021 to regulate ships built before the EEDI became effective for new vessels. The EEXI sets mandatory energy efficiency performance standards for existing ships to achieve specific energy efficiency targets.

Key Features of EEXI:

- The EEXI sets performance standards through analysis of ship design elements and operational characteristics including deadweight tonnage (DWT) and engine power and speed and fuel consumption. Ships need to show EEXI compliance through achievement of the predetermined efficiency standards.
- The EEXI framework requires ships to undergo verification procedures which confirm their compliance status. The verification process includes onboard measurements together with documentation and assessments performed by recognized organizations.

The EEXI system motivates ship operators to implement energy-saving technologies and operational practices which enhance vessel energy efficiency while decreasing fuel usage.

3.2 *Carbon Intensity Indicator (CII)*

The CII represents another regulatory tool which the IMO established through its climate strategy. The CII differs from EEXI because it evaluates operational carbon intensity of vessels through a complete assessment of their GHG emissions during operation. The CII system works to drive ships toward better carbon intensity performance throughout successive years.

Key Features of CII

- The CII calculates ship carbon intensity through operational assessment by dividing total annual CO_2 emissions by distance travelled (gCO_2/ton-mile). The operational efficiency and environmental performance of a vessel become evident through this specific metric.
- The CII rating system will operate annually to sort ships into five performance categories which range from "A" (best performance) to "E" (poor performance). The rating system will be disclosed to ship operators and stakeholders to promote transparency and accountability.
- The CII system requires ships to meet annual improvement targets that lead to better carbon intensity ratings. The system drives operators to develop better practices and innovative solutions through its continuous improvement approach.

3.3 *Correlations Between EEXI and CII Regulations*

The EEXI and CII regulations work together to boost ship energy efficiency while minimizing GHG emissions. The EEXI targets existing ship technical designs and operational efficiency yet the CII measures operational performance through carbon intensity metrics. These regulations establish a complete system to enhance vessel environmental performance from construction through operation and decommissioning.

The simultaneous execution of EEXI and CII regulations produces beneficial effects that enhance both energy efficiency and reduce emissions. A ship which meets its EEXI standards through energy-saving technology implementation will achieve superior operational results which results in an improved CII score. Ship operators who demonstrate strong CII performance tend to meet EEXI standards because operational efficiency has become their main priority.

The shipping industry benefits from a complete emissions reduction strategy through the joint implementation of EEXI and CII regulations. The dual focus on technical and operational vessel performance through these regulations motivates operators to select multiple methods for improving energy efficiency. Ship operators can achieve EEXI compliance through vessel retrofits of energy-saving technologies and operational optimization and effective biofouling management for drag reduction and fuel efficiency improvement.

Biofouling stands as a major obstacle which affects both ship energy efficiency and greenhouse gas emissions. The formation of marine organisms on ship hulls results in drag resistance which increases fuel usage and produces more GHG emissions. The proper management of biofouling helps ships meet EEXI standards while advancing the overall goal of emissions reduction.

4 INVASIVE SPECIES

The introduction and spread of invasive aquatic species pose significant threats to marine ecosystems and economies worldwide. Shipping activities lead to these invasions mainly through two vectors which include ballast water discharge and hull biofouling. The International Maritime Organization’s Ballast Water Management Convention (BWM Convention) has established regulations for ballast water yet hull fouling remains an unregulated yet equally dangerous pathway.

The global shipping industry functions as a primary channel for invasive aquatic species to enter new ecosystems which leads to native biodiversity disruption and functional ecosystem changes and major economic damage. These invasions occur through two main pathways which include ballast water discharge and hull fouling. Ship stability ballast water transports planktonic and larval organisms while hull fouling enables microorganisms and algae and larger invertebrates to attach and grow on submerged ship surfaces including sea chests and propeller shafts and rudders.

The International Maritime Organization established the Ballast Water Management Convention (BWM Convention) in 2004 which entered into force in 2017 to establish rules for ballast water treatment and invasive species control. The regulatory framework does not effectively address hull fouling despite its established role in bio invasions.

4.1 *Species Spread and Environmental Impact*

The hull fouling process enables the distribution of multiple invasive species including algae and bryozoans and barnacles and mussels. The Asian green mussel (Perna viridis) has become a global invasive species because it travels through hull fouling which competes with native bivalves and transforms local ecosystems. The spread of invasive species through hull fouling occurs mainly through recreational vessels because these vessels travel frequently and lack sufficient antifouling protection [9]. Hull fouling leads to 80% of marine invasions in certain areas because Hawaii's stable water temperatures enable fouling communities to survive during transportation [10]. The biofouling community serves as a habitat for pathogenic bacteria including Vibrio cholerae which poses risks to human health.

The process of hull fouling cleaning under water takes place in ports which lack proper systems for disposing biofouling waste. The practice of releasing invasive species into local waters during cleaning operations eliminates any potential advantages of the process [11]. The implementation of insufficient antifouling coatings because of TBT biocide restrictions has resulted in higher fouling rates mainly affecting recreational boats [11]. The global fleet contains recreational vessels which represent only 10-15% of its tonnage yet these vessels lead most invasions because they travel short distances and receive insufficient antifouling maintenance [9].

4.2 *Regulatory Measures and Post-Convention Impact*

The BWM Convention established ballast water as the primary method through which invasive aquatic species entered the global environment before its implementation. Ships transferred massive amounts of ballast water which contained various planktonic organisms together with larvae and cysts. The Great Lakes experienced an invasion of zebra mussels (Dreissena polymorpha) because of ballast water exchanges which caused both environmental damage and annual economic losses exceeding $200 million [12].

The BWM Convention requires ships to use ballast water treatment systems which minimize the number of living organisms discharged to specific performance standards. The implementation of ballast water regulations in 2017 has led to better compliance which has resulted in a significant decrease of new species invasions [12]. The adoption of new technologies and enforcement of regulations faces ongoing challenges mainly in developing regions.

Ballast water management has decreased its role in species introductions yet hull fouling continues to serve as an ongoing and poorly regulated entry point for invasive species. Research shows that fouling organisms survive better during voyages because they stick to hull surfaces and find protective niches [13]. The fouling community differs from ballast water planktonic organisms because it contains sessile and encrusting species which can establish themselves in new environments.

The Hawaiian Islands have documented hull fouling as the primary cause of 80% new marine invasive species introductions while ballast water accounts for only 20% 10].

4.3 *Environmental and Economic Concerns*

Ship hull biofouling presents dual challenges to vessel efficiency and performance yet produces extensive ecological damage with major economic impacts. The movement of vessels between different regions enables them to carry invasive species as hull passengers. The introduced invasive species create ecological disturbances which result in severe damage to biodiversity together with negative impacts on fisheries and tourism. Biofouling presents a significant economic problem through invasive species distribution which affects multiple sectors requiring prompt intervention and action. The economic effects of invasive species create multiple levels of impact.

4.3.1 *The fisheries and aquaculture industry*

The fisheries and aquaculture industry faces major problems because invasive species compete with native species for both resources and living space. The introduction of zebra mussels into native habitats caused population declines in fish species which negatively impacts commercial and recreational fishing activities. The economic damage from zebra mussels in the Great Lakes area totals more than $500 million each year because they harm fish populations and require costly management strategies [14].

4.3.2 *The tourism industry*

The tourism industry depends heavily on coastal areas as its main economic source. Natural habitats become degraded when invasive species spread because it results in reduced biodiversity together with decreased ecosystem visual appeal. The Caribbean faces economic damage from tourism due to lionfish invasions because these invasive species harm native fish and disrupt recreational diving and fishing activities. The lionfish invasion threatens to reduce Caribbean diving industry revenue by $1.2 million annually [15].

4.3.3 *The infrastructure*

The infrastructure together with maintenance expenses experience substantial financial damage because of invasive species particularly affecting water systems and ports. The blockage of pipes by invasive mollusk biofouling results in elevated maintenance costs and operational disruptions for water infrastructure. The control measures for zebra mussel infestations in water intake systems require utilities to spend millions each year which will total $1 billion across all affected regions [14].

4.3.4 *Biodiversity Loss*

The introduction of invasive species can lead to the decline or extinction of native species, reducing biodiversity. Biodiversity value proves difficult to measure economically yet produces long-lasting effects on ecosystem services which include pollination along with nutrient cycling and environmental resilience. The disappearance of biodiversity weakens ecological systems and reduces their ability to generate productive outcomes that support agricultural and forestry activities.

The Great Lakes demonstrate how invasive species spread by biofouling produces substantial economic effects. The Great Lakes experienced severe ecological and economic difficulties after zebra mussels established themselves in the 1980s. The quick multiplication of these mussels coupled with their powerful water filtering abilities has dramatically transformed the ecosystem which now threatens fish species and water purity.

The total financial damage caused by zebra mussels in the Great Lakes amounts to more than $5 billion.

Table 1. Examples of Invasive Species and Their Impact

Species	Vector(s)	Region	Ecological Impact	Economic Impact
Zebra mussel (D. polymorpha)	Ballast water & hull fouling	Great Lakes, North America	Displacement of native species, water quality decline	>$200 million/year in infrastructure and fisheries losses [11]
Asian green mussel (Perna viridis)	Hull fouling	Coastal Asia, Australia, Americas	Competition with native bivalves, fouling of infrastructure	Significant damage to aquaculture and shipping infrastructure [11]
Sea lamprey (Petromyzon marinus)	Ballast water	Great Lakes, North America	Predation on native fish, ecosystem imbalance	Decline in commercial fish stocks, costly control programs
Styela clava (sea squirt)	Hull fouling	Europe, New Zealand	Fouling of aquaculture equipment, competition with native species	Economic losses in shellfish farming [13]

The worldwide distribution of invasive aquatic species primarily occurs through shipping activities. The BWM Convention has successfully reduced ballast water-related invasions yet hull fouling continues to transfer invasive organisms that cause major ecological and economic damage. The solution requires immediate action to tackle the problems of niche areas and ineffective cleaning practices and unregulated biofouling waste discharge. A complete international framework for hull fouling management needs to work alongside ballast water regulations to protect marine ecosystems and economies.

5 FUEL CONSUMPTION, GHG EMISSIONS, AND EEXI COMPLIANCE

The maritime industry faces mounting pressure to decrease greenhouse gas (GHG) emissions because of international regulations that include the Energy Efficiency Existing Ship Index (EEXI). The presence of hull biofouling stands as a crucial element which affects both vessel fuel efficiency and emission levels because it creates drag that increases fuel usage. This paper investigates the relationship between ship hull biofouling and its effects on fuel consumption and GHG emissions while analysing the consequences for EEXI compliance.

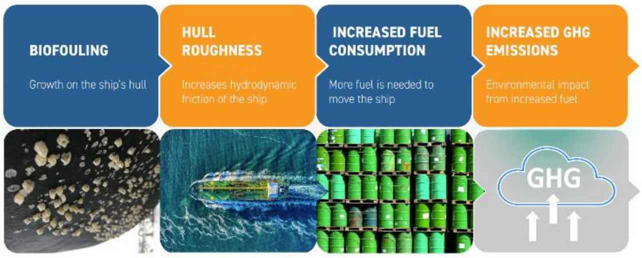

Figure 2. The ship hull biofouling [5]

5.1 *Impact on Hydrodynamics*

The hull experiences changes in hydrodynamic properties because of biofouling which results in increased resistance when the vessel navigates through water. The surface roughness from fouling causes significant fuel consumption increases because small changes in roughness lead to major drag increases. The study conducted by Song demonstrated the following results:

- Light fouling (1-2 mm): Increases fuel consumption by approximately 10-15%.
- Moderate, the fuel consumption rises by 20-25% when fouling reaches the moderate stage between 2-5 mm.
- Heavy fouling (>5 mm) leads to a 30-40% increase in fuel consumption [16].

5.2 *Fuel Consumption and GHG Emissions*

The maritime industry faces a major challenge because ships' hull biofouling affects fuel consumption which in turn affects greenhouse gas (GHG) emissions as measured by the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII). The accumulation of marine organisms on ship hulls produces frictional resistance which increases fuel consumption and results in higher GHG emissions. The Journal of Ship Research published research showing that 10% hull roughness from biofouling leads to 6.5% increased fuel consumption [17]. The International Maritime Organization (IMO) conducted research which demonstrated that biofouling leads to a maximum 20% increase in fuel consumption together with a maximum 15% increase in GHG emissions (IMO, 2020). The EEXI and CII regulations focus on smooth hull maintenance because it helps ships reduce their fuel consumption and emissions. A ship with high EEXI rating needs to adopt either hull cleaning or anti-fouling coating application as biofouling reduction measures. Ships that decrease their biofouling levels will use less fuel while producing fewer GHG emissions which leads to economic benefits and environmental protection. The National Oceanic and Atmospheric Administration (NOAA) conducted research which demonstrated that biofouling reduction enables ships to conserve 3.8

million tons of fuel annually which translates to 12.1 million tons of CO_2 emission reduction [18]

Multiple research studies have established the quantitative effects of biofouling on fuel usage and greenhouse gas emissions. The following table presents findings from different studies about how hull fouling affects fuel consumption and emissions:

Table 2. Impact of Hull Biofouling on Fuel Consumption and GHG Emissions [16,19,20,23]

Study	Hull Fouling Level	Fuel Consumption Increase (%)	GHG Emissions Increase (%)
Song et al. (2020)	Light (1-2 mm)	10-15%	3-4%
Demirel et al. (2019)	Moderate (2-5 mm)	20-25%	6-8%
Atlar et al. (2018)	Heavy (>5 mm)	30-40%	9-12%
Wang et al. (2021)	Moderate to Heavy	25-35%	8-10%

5.3 *Case Study Analysis of Fuel Consumption and GHG Emissions*

The impact of hull fouling on fuel consumption can be summarized as follows:

- Light Fouling (1-2 mm): Increased fuel consumption by 10-15%.
- Moderate Fouling (2-5 mm): Increased fuel consumption by 20-25%.
- Heavy Fouling (>5 mm): Increased fuel consumption by 30-40 [23].

Table 3. Case Study Analysis of Fuel Consumption and GHG Emissions

Fouling Level	Fuel Consumption (tons/day)	Ship Speed (knots)	GHG Emissions (tons CO2/day)
Light (1-2 mm)	30	14	80
Moderate (2-5 mm)	37	12	95
Heavy (>5 mm)	45	10	110

5.3.1 *Calculation of GHG Emissions*

To calculate GHG emissions, the following formula was used:

GHG Emissions=Fuel Consumption×Emission Factor

The emission factor for marine diesel oil is approximately 2.67 kg CO_2 per liter of fuel. Given that 1 ton of marine diesel is approximately 1.025 cubic meters, and at an average density of 850 kg/m^3, the fuel consumption in liters can be converted as follows:

- For light fouling:

Fuel Consumption: =30 tons/day × 1,000 kg/ton/850 kg/m3 ≈ 35.29 m3/day ≈ 35,290 liters/day

GHG Emissions: =35,290 liters/day × 2.67 kg CO2/liter ≈ 94,300 kg CO2/day ≈ 80 tons CO2/day

- For moderate fouling:

Fuel Consumption: =37 tons/day × 1,000 kg/ton/850 kg/m3 ≈ 43.53 m3/day ≈ 43,530 liters/day

GHG Emissions: =43,530 liters/day × 2.67 kg CO2/liter ≈ 116,000 kg CO2/day ≈ 95 tons CO2/day

- For heavy fouling:

Fuel Consumption: =45 tons/day × 1,000 kg/ton/850 kg/m3 ≈ 52.94 m3/day ≈ 52,940 liters/day

GHG Emissions: =52,940 liters/day × 2.67 kg CO2/liter ≈ 141,000 kg CO2/day ≈ 110 tons CO2/day

The case study results show a direct relationship between biofouling and both fuel consumption and GHG emissions. The change from light to heavy fouling caused fuel consumption to rise by 50% and GHG emissions to increase by 37.5%. The results demonstrate that proper biofouling management stands as a critical factor for achieving EEXI standards compliance.

5.4 *Implications for EEXI and CII Compliance*

The maritime industry faces challenges in EEXI and CII regulation compliance because biofouling affects both fuel efficiency and emissions performance. Vessels that experience major fouling issues will find it difficult to achieve required energy efficiency standards which could lead to penalties and higher operational expenses. The EEXI score of a vessel depends directly on its fuel consumption rates. Biofouling-related drag increases fuel consumption which could result in EEXI standard non-compliance.

The CII rating becomes challenging to achieve because biofouling increases total CO_2 emissions per ton-mile. The rise in fuel consumption because of biofouling creates challenges for vessels to reach their required CII rating.

Non-compliance with EEXI and CII regulations results in financial penalties together with higher insurance costs and reduced chartering possibilities. The higher fuel expenses from increased consumption create substantial financial challenges for shipowners who operate their vessels. The cost impact of biofouling varies between $1,000 and $4,000 daily [20] based on vessel dimensions and fouling severity. The financial impact of biofouling damages both profitability and sustainability initiatives in maritime operations.

The maritime industry needs to understand the essential link between ship hull biofouling and its effects on fuel consumption and greenhouse gas emissions. The analysis of empirical data and case studies shows that fouling growth results in increased fuel usage which produces higher GHG emissions. The shipping industry can achieve better operational efficiency and reduced environmental impact through effective biofouling management strategies. The industry needs to continue developing antifouling technologies and practices to solve this critical challenge.

6 STRATEGIES TO MINIMIZE BIOFOULING ON SHIPS

Biofouling represents a major maritime challenge because it forms when microorganisms together with plants algae and animals settle on underwater surfaces. A successful biofouling management system requires the integration of monitoring and assessment and intervention strategies. The International Maritime Organization (IMO) has established guidelines for biofouling management which promotes ships to create Biofouling Management Plans (BMPs).

These plans should include:
- Risk Assessment: The evaluation of biofouling risk depends on ship operational data including trading routes and layup periods.
- The implementation of monitoring systems should include underwater drone or remotely operated vehicle (ROV) technologies to assess hull biofouling status.
- Cleaning Schedule: The biofouling risk assessment and monitoring results should determine the frequency of proactive cleaning operations.

6.1 *Tools and equipment for biofouling management on ships*

Multiple tools and equipment exist for biofouling management on board vessels.
- The modern anti-fouling paint market includes two main categories: biocide-based coatings and non-toxic silicone-based coatings which prevent organisms from sticking to hull surfaces. Research shows that vessels equipped with advanced anti-fouling systems achieve fuel consumption reductions.
- Air bubble systems represent an advanced method for managing biofouling. The continuous bubble curtain surrounding the hull or specific areas prevents fouling organisms from settling. The operation of air bubble systems depends on two main mechanisms. Physical disruption: the water column becomes turbulent because of bubbles which prevents organisms from settling on surfaces. Increased Water Flow: the bubbles create improved water flow which prevents stagnant water conditions that lead to fouling. The installation of air bubble systems in sea chests and cooling water intakes enables operators to maintain optimal operational conditions while reducing fouling.
- The use of In-Water Cleaning Systems enables vessel operators to remove biofouling through automated hull cleaning systems that function without requiring dry docking. The systems use brushes together with suction mechanisms to perform hull cleaning operations when vessels remain operational.

6.2 *Monitoring and Assessment Tools*

The management of biofouling requires continuous monitoring and assessment practices. Technologies include:
- Underwater Drones and ROVs: These vehicles use high-resolution cameras and sonar to inspect hull surfaces and niche areas which enables real-time fouling level monitoring.
- Biofouling Sensors: Sensors enable the detection of fouling organisms and water quality parameter monitoring which leads to prompt intervention actions. Some systems have built-in alert functions that notify operators when fouling reaches specific threshold levels.
- Data Analytics Platforms: Ship operators can track fouling trends through time by using data analytics platforms. Operators can enhance their cleaning schedules and operational adjustments through historical data analysis.

6.3 *Proactive vs. Reactive Cleaning*

Biofouling management requires a fundamental understanding of proactive versus reactive cleaning methods.
- Proactive Cleaning follows a maintenance schedule which relies on monitoring data and risk assessments for its implementation. The preventive approach stops heavy fouling buildup which leads to lower maintenance requirements and decreased expenses.
- Reactive Cleaning takes place after substantial biofouling formation leads to expensive dry docking procedures and thorough cleaning operations. The cleaning process through this method results in longer periods of inactivity and environmental damage because it requires releasing contaminants during the cleaning process

7 CONCLUSIONS

The international regulatory framework regarding biofouling and GHG emissions is evolving to address the pressing environmental challenges faced by the shipping industry. The EEXI serves as a critical measure to enhance energy efficiency and mitigate emissions, while effective biofouling management plays a vital role in achieving compliance with these standards. The shipping sector can achieve substantial GHG emission reductions through investments in cleaner technologies and operational efficiency improvements and regulatory strengthening and collaborative efforts. The industry can achieve both ship energy efficiency improvement and pollution prevention through effective biofouling control measures which support global climate change mitigation and marine ecosystem protection efforts.

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