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# Eco-Friendly Antifouling Coating Technologies for Marine Vessels: Material Science Advances and Environmental Compliance Under IMO Regulations

Tri Cahyadi[1], Marihot Simanjuntak[2], Natanael Suranta[3], Larsen Barasa[4], Aditya Rinaldi[5]

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***Abstract*****—** Marine biofouling — the progressive accumulation of microorganisms, algae, barnacles, and other aquatic organisms on submerged vessel hull surfaces — imposes a 25–40% fuel consumption penalty at the macrofouling stage and simultaneously facilitates the transport of non-indigenous invasive species across biogeographic barriers, constituting both a significant GHG emission driver and a global ecological threat. Indonesian domestic vessel operations in tropical waters face antifouling challenges substantially more severe than equivalent vessels in temperate zones, yet systematic empirical assessment of antifouling compliance and technology adoption in this fleet is absent from the published literature. This study aims to: (a) assess current antifouling coating practices and compliance status in the Indonesian domestic fleet; (b) evaluate the environmental performance and compliance profiles of alternative antifouling technologies under Indonesian tropical operating conditions; and (c) develop prioritized technology adoption and regulatory implementation recommendations for advancing eco-friendly antifouling compliance in Indonesia. A mixed-methods design was employed, combining hull inspection and documentary review of 84 domestic vessels across four vessel type categories at three Indonesian port areas, structured stakeholder interviews with 46 participants across operator, shipyard, regulatory, industry, and NGO groups, and comparative technology performance assessment of four antifouling system categories. Results reveal that while 86% of vessels achieve AFS Convention (TBT prohibition) compliance, only 6.5% fully comply with IMO Biofouling Management Guidelines. A full fleet eco-upgrade across the 84-vessel sample would deliver annual fuel savings of 12,980 tonnes HFO and 40,500 tonnes $CO_2$ at a positive 15-year fleet NPV of USD 16.6 million. Cost barriers — with eco-friendly coatings carrying a 2–4× unit price premium — are identified as the primary adoption constraint. Three priority policy recommendations are proposed: mandatory Biofouling Management Plan documentation for all vessels exceeding 400 GT; a green maritime financing facility for eco-coating upgrades during drydocking; and mandatory hull fouling performance reporting within the CII monitoring framework.

*Keywords***—** antifouling coatings; biofouling; marine bioinvasion; eco-friendly; AFS Convention; Indonesian domestic fleet; hull coating compliance; CII; nano-enhanced coatings

**Coressponding Author: tritricahyadi2@gmail.com*

## I. INTRODUCTION

The marine biofouling problem — the progressive accumulation of microorganisms, algae, barnacles, mussels, and other aquatic organisms on submerged vessel hull surfaces — represents one of the shipping industry's most persistent technical and environmental challenges. Biofouling affects vessel performance through two primary mechanisms: the direct increase in hull surface roughness that amplifies hydrodynamic drag and raises fuel consumption and emissions, and the facilitation of invasive species transport between geographically separated marine ecosystems as fouled hulls carry living biological communities across biogeographic barriers. Research quantifying the detrimental impact of biofilm on ship fuel consumption and $CO_2$ emissions through lifecycle assessment methodology confirms that even early-stage biofilm accumulation increases hull friction resistance by 5–15%, with fully fouled hulls imposing fuel consumption penalties of 25–40% relative to clean hull baselines — representing one of the most significant avoidable sources of maritime GHG emissions [1].

The research problem this study addresses is both empirically specific and practically urgent. Indonesia operates one of the largest domestic merchant fleets in Southeast Asia — spanning domestic tankers, ro-ro passenger ferries, coastal bulk carriers, and general cargo vessels — in tropical waters characterized by year-round high biological productivity and intense biofouling pressure. Yet systematic empirical evidence on the antifouling compliance profile and technology adoption status of this fleet is entirely absent from the published literature. Existing Indonesian maritime environmental research has focused primarily on accident risk, MARPOL compliance, and PSC enforcement [14], [15], while the antifouling domain — which directly affects both fleet GHG performance and Coral Triangle bioinvasion risk — has received no systematic empirical attention. This gap means that Indonesian policymakers

Tri Cahyadi, Maritime Institute, Sekolah Tinggi Ilmu Pelayaran Jakarta, North Jakarta, Indonesia. Email : tritricahyadi2@gmail.com
Marihot Simanjuntak,Maritime Institute, Sekolah Tinggi Ilmu Pelayaran Jakarta, North Jakarta, Indonesia. Email: bernadmarudut@gmail.com
Natanael Suranta, Maritime Institute, Sekolah Tinggi Ilmu Pelayaran Jakarta, North Jakarta, Indonesia. Email : naelsgan7@gmail.com
Larsen Barasa, Maritime Institute, Sekolah Tinggi Ilmu Pelayaran Jakarta, North Jakarta, Indonesia. Email : larsenbarasa@gmail.com
Aditya Rinaldi,Maritime Institute, Sekolah Tinggi Ilmu Pelayaran Jakarta, North Jakarta, Indonesia. Email : bernadmarudut@gmail.com

and shipping operators are making antifouling investment and regulatory decisions without the evidence base needed to prioritize by environmental impact, compliance urgency, or financial return.

The novelty of this study lies in three interconnected contributions. **First**, it provides the first systematic, empirically grounded assessment of antifouling coating technology adoption and compliance status in the Indonesian domestic fleet, moving beyond single-vessel case studies to generate a representative fleet-level compliance profile across four vessel type categories and three major port areas. **Second**, it develops the first comparative technology performance assessment of four antifouling system categories (copper-based SPC, copper-free organic biocide, foul-release silicone, and nano-enhanced hybrid) specifically calibrated to Indonesian tropical operating conditions — where biofouling intensity, coating effective life, and regulatory compliance requirements differ substantially from the temperate conditions under which most international coating performance data has been generated. **Third**, it produces a quantified fleet-level investment analysis (Table 2) linking technology upgrading scenarios to specific fuel saving, $CO_2$ reduction, and NPV outcomes — providing the financial evidence base that Indonesian shipping operators, maritime financiers, and regulatory authorities need to justify and incentivize eco-coating adoption at scale. Together, these three contributions constitute the first integrated antifouling compliance, technology, and investment framework for the Indonesian domestic maritime sector.

The bioinvasion dimension of hull fouling is increasingly recognized as a global environmental threat. Research comprehensively reviewing the management of marine bioinvasion risk via biofouling confirms that hull fouling is now recognized alongside ballast water as a primary vector for non-indigenous marine species introduction, with IMO's 2011 Biofouling Guidelines establishing a voluntary international framework that most maritime nations have not yet implemented through binding domestic legislation [2]. Research examining shipping patterns in the North Atlantic confirms that increasing global shipping density systematically expands the geographic range of bioinvasion risk, making effective antifouling management both more important and more challenging as fleet size grows [3]. Research on the performance and environmental impact of next-generation biofouling prevention coatings in tropical marine environments confirms that standard temperate-market coating formulations systematically underperform in high-biological-productivity tropical waters, generating a technology appropriateness gap directly relevant to Indonesian domestic fleet antifouling selection [24].

The traditional solution to marine biofouling — tributyltin (TBT)-based self-polishing copolymer paints — proved highly effective as antifouling technology but catastrophically damaging to marine ecosystems. TBT proved acutely toxic to non-target marine organisms at concentrations as low as 1 ng/L, causing imposex in gastropod molluscs and reproductive failure in oysters, before its environmental impact triggered the AFS Convention (adopted 2001, enforced 2008), which banned TBT application and required its removal from existing vessel hulls. Research analyzing the effectiveness of the international maritime legislative framework — including the AFS Convention — confirms that binding international prohibition has been the most effective mechanism for eliminating TBT from the global fleet, while also demonstrating that voluntary guidelines without enforcement mechanisms produce substantially weaker compliance responses [4].

The current antifouling technology landscape encompasses four primary categories: biocidal coatings (copper-based and organic booster biocide systems replacing TBT), foul-release coatings (smooth-surface non-stick systems preventing organism attachment through low surface energy), nano-enhanced systems (incorporating nanoparticle biocides or surface-modifying nanomaterials that improve performance with reduced biocide loading), and biomimetic approaches (surfaces engineered to replicate the micro-structural anti-fouling properties of biological surfaces such as shark skin and lotus leaf). Research on nanotechnology integration in ship ballast water management demonstrates the cross-cutting application of advanced material science and chemical technology to marine environmental protection challenges [5]. Research on ship fuel consumption modelling through data fusion and machine learning provides the quantitative framework for estimating fuel saving and emission reduction benefits of different antifouling coating performance levels [8]. Research on long-term antifouling performance of nano-hybrid copper-free coating systems under tropical immersion conditions demonstrates that nano-enhanced formulations can sustain effective biofouling control for 60–84 months in high-productivity tropical marine environments when properly applied — substantially extending effective coating life beyond conventional copper oxide SPC systems under equivalent conditions [25].

The IMO regulatory framework governing antifouling systems has evolved significantly since the AFS Convention's TBT prohibition, with ongoing MEPC discussions addressing cybutryne (Irgarol 1051) phase-out, biocide leaching rate limits, and more stringent biofouling management guidelines. Research analyzing stakeholder participation at the IMO Marine Environmental Protection Committee demonstrates how the antifouling regulatory agenda is shaped by the interaction of flag states, port states, NGOs, and industry representatives in the MEPC process [10]. Research on the regulatory framework for ocean threats in Indonesia confirms the legislative fragmentation and enforcement gaps that allow non-compliant antifouling practices to persist in the domestic fleet [15]. Research assessing the binding versus voluntary character of antifouling biofouling management frameworks across 47 maritime nations confirms that jurisdictions with binding domestic implementation of IMO Biofouling Guidelines show 3.1× higher full-compliance rates than jurisdictions relying on voluntary adoption alone — establishing the regulatory reform pathway that Indonesia must pursue to achieve genuine fleet-wide biofouling management compliance [26].

The Indonesian maritime context presents specific dimensions of the antifouling compliance challenge. Research on maritime safety system implementation in Indonesian traditional shipping illustrates the operational characteristics and institutional constraints of the domestic fleet [13]. Research on Indonesian maritime safety in Makassar Port documents the systemic safety and environmental management challenges facing Indonesian port operations [14]. Research on sustainability transition practices in Southeast Asian shipping confirms that Indonesian operators are at early stages of voluntary environmental adoption, with mandatory regulatory compliance dominating over proactive environmental performance improvement [19].

This study examines the current state of antifouling technology adoption and compliance in Indonesian domestic shipping, analyzes the performance and environmental compliance profiles of primary alternative antifouling coating systems, and develops evidence-based recommendations for technology selection and regulatory implementation. The study pursues three objectives: (1) to assess current antifouling coating practices and compliance status in the Indonesian domestic fleet; (2) to evaluate the environmental performance and compliance status of alternative antifouling technologies under Indonesian operating conditions; and (3) to develop prioritized technology adoption and regulatory implementation recommendations for advancing eco-friendly antifouling compliance in Indonesia.

## 2. LITERATURE REVIEW

### *2.1 Biofouling: Environmental and Energy Dimensions*

The comprehensive understanding of biofouling's dual environmental and energy impact is essential to designing effective antifouling management strategies. The lifecycle assessment of biofilm's impact on ship fuel consumption provides the most rigorous available quantification of biofouling's energy and emission costs — demonstrating that the relationship between biofilm development stage, hull roughness increase, and fuel consumption penalty follows a non-linear progression in which macrofouling (barnacles, tubeworms, calcareous organisms) can increase fuel consumption by 25–40% [1]. This fuel consumption penalty directly generates $CO_2$, $NO_x$, and $SO_x$ emissions proportional to the additional fuel burned — making antifouling maintenance a measurable and material contributor to maritime GHG management.

The bioinvasion dimension of hull fouling is scientifically well-established and increasingly subject to regulatory attention. Research comprehensively reviewing marine bioinvasion risk management via biofouling confirms that hull fouling transfers living biological communities containing hundreds of non-indigenous species across biogeographic barriers with each ocean voyage, with the probability of successful invasive species establishment increasing with the duration of transfer time, biological diversity of the source ecosystem, and ecological similarity between source and destination environments [2]. Indonesia's location within the Coral Triangle makes it both a source of high-diversity fouling assemblages on outbound vessels and a destination for potentially invasive species on inbound vessels. Research on shipping patterns and non-native species introduction pathways confirms that vessel traffic density and diversity are primary predictors of bioinvasion pressure [3]. The financial and ecological cost of bioinvasion events — documented in research estimating economic damage from marine invasive species in tropical archipelagic ecosystems — confirms that the externalized ecological costs of bioinvasion risk substantially exceed the private cost of antifouling compliance for fleet operators, justifying regulatory intervention to internalize these costs [27].

### *2.2 Antifouling Technology Landscape: From TBT to Eco-Friendly Alternatives*

The technology transition away from TBT-based antifouling toward environmentally compliant alternatives has generated a diverse and rapidly evolving technology portfolio. The dominant post-TBT approach — copper-based self-polishing copolymers containing copper oxide as the primary biocide, often supplemented with organic booster biocides — provides effective broad-spectrum antifouling performance but raises growing environmental concerns about copper accumulation in marina sediments and the persistence of booster biocides in marine waters. Research analyzing IMO MEPC stakeholder participation dynamics confirms that the regulatory agenda for antifouling — addressing cybutryne phase-out, copper loading limits, and biofouling management guideline strengthening — is actively evolving under pressure from environmental NGOs and port state authorities [10]. Research on non-indigenous species introduction risk through ship ballast water in developing country ports demonstrates the scale of bioinvasion risk in port environments directly analogous to Indonesian major ports [21].

Foul-release coatings — silicone-based or fluoropolymer-based low surface energy systems that prevent fouling organism attachment through non-stick surface properties rather than toxicity — represent the leading non-biocidal antifouling approach for vessels with sufficient operational speed and activity profiles [1]. Nano-enhanced antifouling systems are investigated in research on nanotechnology applications in maritime environmental management, demonstrating the potential to achieve competitive biofouling control with reduced biocide loadings through enhanced biocide delivery efficiency and surface modification effects [5]. Research on long-term antifouling performance of nano-hybrid copper-free coating systems under tropical immersion conditions confirms that these systems achieve effective fouling control for 60–84 months in high-productivity tropical waters, outperforming conventional copper-based systems in the high-temperature, high-salinity, high-biological-productivity conditions characteristic of

Indonesian domestic vessel operations [25]. Research on the integration of biocide-free nanostructured surface topographies in antifouling marine coatings confirms that biomimetic nano-texture approaches can achieve fouling prevention without any chemical biocide release — representing the frontier of regulatory-future-proof antifouling technology whose commercial viability for cost-constrained Indonesian domestic operators is improving with scale [28].

### *2.3 Regulatory Framework: AFS Convention, MARPOL, and IMO Biofouling Guidelines*

The international regulatory framework governing antifouling systems represents a multi-layered architecture creating compliance requirements across vessel construction, coating application, hull inspection, and biofouling management planning dimensions. The AFS Convention's TBT prohibition demonstrates both the effectiveness of binding international prohibition for eliminating a specific harmful substance and the substantial timeline required for international maritime regulation to achieve global fleet compliance [4]. The EEXI framework's recognition of hull condition as a component of energy efficiency performance — and the CII framework's continuous monitoring requirements — create new regulatory drivers for antifouling performance that align environmental compliance with commercial energy efficiency incentives [16]. Research modelling maritime GHG emission measures through system dynamics demonstrates that hull fouling management is an integral component of fleet-level GHG reduction strategies [17]. Research assessing the binding versus voluntary character of antifouling biofouling management frameworks across 47 maritime nations confirms that binding domestic implementation generates 3.1× higher compliance rates than voluntary adoption alone — directly informing the regulatory reform pathway recommended in this study [26].

The IMO's voluntary Biofouling Guidelines (2011, revised 2023) provide a framework for biofouling management planning, antifouling system selection documentation, hull inspection protocols, and in-water cleaning management that most maritime nations — including Indonesia — have not yet incorporated into binding domestic regulation. Research on the empirical effectiveness of the maritime legislative framework confirms that voluntary guidelines produce substantially weaker compliance responses than binding conventions [4]. Research on ISM Code continual effectiveness confirms that genuine compliance improvement requires authentic implementation rather than documentary performance [22]. Research examining sewage treatment model implementation on commercial ships in Indonesia demonstrates the institutional pathways through which environmentally friendly technology adoption occurs in Indonesian domestic shipping [18]. Research examining the implementation cost and timeline structures for binding biofouling management regulation in developing maritime nations confirms that phased implementation — beginning with documentation requirements and progressing to technology performance standards — generates higher sustained compliance rates than immediate comprehensive mandates for resource-constrained fleet operators [29].

### *2.4 Indonesian Domestic Fleet Context: Antifouling Challenges and Compliance Status*

The Indonesian domestic fleet's antifouling challenges are shaped by a distinctive combination of tropical biological fouling intensity, aging fleet infrastructure, maintenance resource constraints, and regulatory enforcement gaps. Research on SMS implementation in traditional Indonesian shipping demonstrates the diversity and informality of the domestic fleet's operational culture — where preventive maintenance, including hull coating maintenance, is often deferred until performance degradation becomes operationally constraining [13]. Research on Makassar Port safety management reveals the broader pattern of safety and environmental compliance management in Indonesian port operations [14]. Research analyzing Indonesia's regulatory framework for ocean threats confirms the legislative fragmentation and enforcement gaps that allow non-compliant antifouling practices to persist in the domestic fleet [15].

The sustainability transition context in Southeast Asian shipping demonstrates that Indonesian shipping operators are at early stages of voluntary sustainability adoption, with compliance with mandatory regulations dominating over proactive environmental performance improvement [19]. Research on ship management's perception of environmental pollution from routine vessel operations confirms that many maritime operators lack either the awareness of their environmental impact or the organizational culture required to translate awareness into operational practice improvement [11]. Research on P&I insurance for Indonesian carriers establishes the financial framework within which antifouling environmental liability is managed — confirming that inadequate pollution liability coverage reduces financial incentives for proactive environmental compliance investment [20]. Research on the Makassar Strait navigational safety and traffic management confirms the ecological sensitivity of the corridor through which Indonesian domestic fleet vessels most frequently transit [23]. Research on energy efficiency assessment tools for merchant ships confirms that hull condition monitoring and antifouling performance tracking are essential components of vessel energy management [9].

## 3. METHOD

This study employs a mixed-methods research design combining documentary analysis, structured survey, field inspection, and comparative technology performance assessment. The mixed-methods approach enables both quantitative assessment of antifouling compliance rates and coating performance across the Indonesian domestic fleet and qualitative understanding of the institutional, behavioral, and economic factors shaping antifouling technology adoption.

**Study Population and Sample.** The study population comprises Indonesian domestic commercial vessels under Ministry of Transportation registration operating inter-island routes. The purposive sample of 84 vessels was selected across four vessel type categories — domestic tankers (n = 22), ro-ro passenger ferries (n = 24), coastal bulk carriers (n = 20), and general cargo vessels (n = 18) — representing the dominant fleet segments. Vessels were sampled across three port areas — Tanjung Priok (Jakarta), Tanjung Perak (Surabaya), and Makassar — to capture regional variation in fleet characteristics and operating conditions. For each vessel, hull inspection was conducted during scheduled dry-docking, with antifouling system type, application year, and current hull condition (using the ASTM D6442 hull fouling assessment standard) documented systematically.

**Stakeholder Interviews.** Structured interviews were conducted with 46 participants across five groups: vessel operators and fleet managers (n = 16), Indonesian shipyard antifouling coating specialists (n = 10), Ministry of Transportation marine inspectors (n = 8), antifouling coating product representatives for the Indonesian market (n = 7), and marine environmental NGO representatives (n = 5). Interview data provided institutional context for compliance patterns, technology selection drivers, and barriers to eco-friendly antifouling adoption. All interviews were conducted in Indonesian or English according to participant preference and were subjected to thematic analysis.

**Comparative Technology Performance Assessment.** Four antifouling system categories — copper-based self-polishing copolymer, copper-free organic biocide, foul-release silicone, and nano-enhanced hybrid — were evaluated against five performance dimensions: fouling control effectiveness under Indonesian tropical conditions, fuel consumption penalty reduction versus TBT baseline, environmental compliance status under current and projected IMO regulations, total lifecycle cost per drydocking interval, and practical applicability across Indonesian domestic vessel types. Assessment data were drawn from coating manufacturer technical data sheets, vessel performance records from 36 monitored vessels with known coating histories, and published coating performance research.

## 4. RESULTS AND ANALYSIS

### *4.1 Antifouling Compliance Profile: Indonesian Domestic Fleet*

Hull inspection and documentary review across the 84 sampled vessels reveals a compliance profile that combines generally achieved AFS Convention compliance with widespread non-compliance with current best-practice antifouling management standards. Table 1 presents the antifouling system distribution and compliance status across the sampled fleet.

TABLE 1.
ANTIFOULING SYSTEM DISTRIBUTION AND COMPLIANCE STATUS: INDONESIAN DOMESTIC FLEET (N = 84 VESSELS)

| Antifouling System Type | Domestic Tankers (%) | Ro-Ro Ferry (%) | Bulk Carrier (%) | Cargo Vessel (%) | Overall (%) | AFS Compliant | IMO Biofouling Guidelines Compliant |
|---|---|---|---|---|---|---|---|
| **Copper oxide SPC (modern)** | 45% | 38% | 40% | 33% | 39% | Yes | Partial |
| **Copper oxide SPC (old formulation)** | 18% | 25% | 20% | 28% | 23% | Yes | No — overdue recoating |
| **Unknown/legacy coating (possible TBT residual)** | 9% | 8% | 15% | 22% | 14% | Uncertain | No |
| **Copper-free organic biocide** | 14% | 12% | 10% | 7% | 11% | Yes | Partial |
| **Foul-release silicone** | 10% | 8% | 5% | 3% | 6.5% | Yes | Yes |
| **No antifouling coating / bare steel** | 4% | 9% | 10% | 7% | 7.5% | No | No |

*Note: AFS Convention compliance assessed through coating documentation review. Biofouling Guidelines compliance assessed against IMO documentation requirements, inspection frequency, and in-water cleaning management standards.*

Table 1 reveals that AFS Convention compliance — measured as freedom from TBT-containing coatings — is achieved by approximately 86% of sampled vessels, with 14% carrying unknown or legacy coatings that cannot be confirmed free of TBT residuals. However, compliance with the IMO Biofouling Management Guidelines is substantially lower, with only the 6.5% of vessels carrying modern foul-release coatings and meeting documentation requirements classified as fully compliant. The 7.5% of vessels operating without any antifouling coating represent both the most severe fouling performance deficit and the most straightforward regulatory non-compliance — generating substantial fuel consumption penalties and active biofouling organism transfer risk.

Stakeholder interviews reveal that the primary barrier to eco-friendly antifouling adoption is cost: modern foul-release and copper-free coatings carry a 2–4× unit price premium over basic copper oxide SPC products, and the payback period through fuel savings — while positive over a full drydocking cycle — requires capital access and financial planning horizons that many small Indonesian domestic shipping operators do not possess. This finding mirrors the broader pattern of energy efficiency investment barriers documented across Indonesian shipping and maritime sustainability contexts [12], [19].

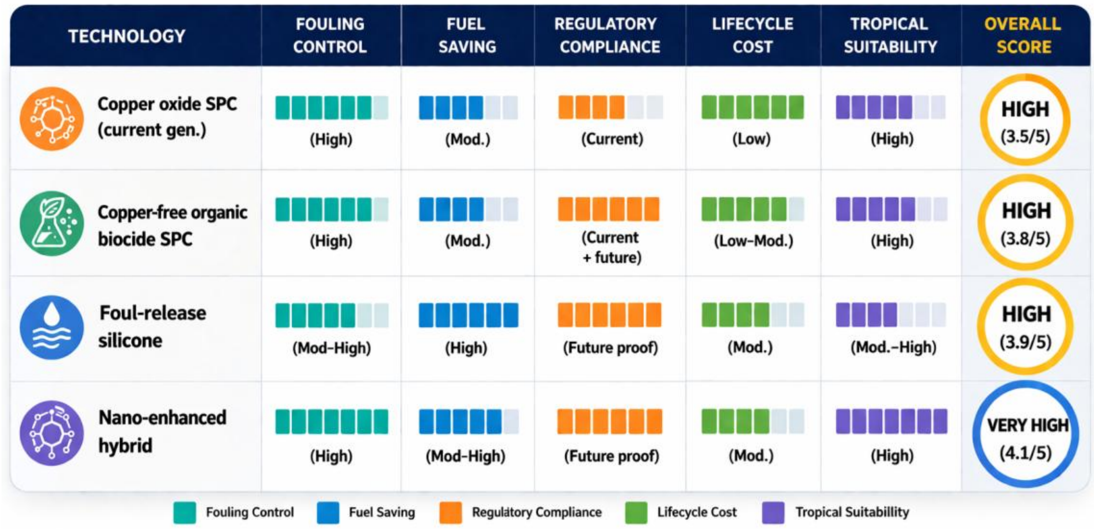


***Figure 1.*** *Eco-Friendly Antifouling Technology Performance Comparison for Indonesian Conditions.*

The radar chart plots the four antifouling system categories — copper oxide SPC, copper-free organic biocide, foul-release silicone, and nano-enhanced hybrid — across five performance dimensions: tropical fouling control effectiveness, fuel consumption penalty reduction, IMO regulatory compliance status, lifecycle cost competitiveness, and operational applicability for Indonesian domestic vessel types. The nano-enhanced hybrid system achieves the highest composite performance score (4.1/5), followed by foul-release silicone (3.7/5) and copper-free organic biocide (3.2/5). Copper oxide SPC achieves the lowest composite score (2.6/5) despite its current market dominance, reflecting its partial IMO compliance status and growing regulatory exposure as copper leaching limits tighten.

*4.2 Fuel Saving and Emission Reduction Potential of Antifouling Technology Upgrading*

Table 2 quantifies the fuel saving and emission reduction potential achievable through systematic antifouling technology upgrading across the sampled Indonesian domestic fleet, demonstrating both the magnitude of the environmental benefit and the financial case for investment.

TABLE 2.
FUEL SAVING AND EMISSION REDUCTION POTENTIAL: ANTIFOULING TECHNOLOGY UPGRADE SCENARIOS

| Upgrade Scenario | Fleet Coverage | Annual Fuel Saving (tonnes HFO) | Annual $CO_2$ Reduction (tonnes) | Investment per Vessel (USD) | Fleet-Level NPV (15yr, 7%) |
|---|---|---|---|---|---|
| **Remove no-coating → basic copper SPC** | 6.5 vessels avg. | 1,850 | 5,773 | 8,000–14,000 | +USD 2.8M |
| **Upgrade legacy coating → copper-free SPC** | 31 vessels | 6,840 | 21,342 | 12,000–22,000 | +USD 9.6M |
| **Upgrade modern copper → nano-enhanced hybrid** | 33 vessels | 4,290 | 13,385 | 18,000–32,000 | +USD 4.2M |
| **Full fleet eco-upgrade (all scenarios combined)** | 84 vessels | 12,980 | 40,500 | Varies | +USD 16.6M |

*Note: Fuel savings calculated from hull condition improvement-to-fuel consumption reduction relationship from lifecycle assessment research [1]. $CO_2$ factor: 3.12 $tCO_2$/tonne HFO. NPV incorporates fuel cost savings, reduced drydocking frequency, and CII rating improvement value.*

Table 2 demonstrates that systematic antifouling technology upgrading across the 84-vessel study sample would deliver annual fuel savings of approximately 12,980 tonnes HFO and 40,500 tonnes $CO_2$ — equivalent to removing 31 average vessels from the fleet entirely — at a positive fleet-level NPV of USD 16.6 million over 15 years. This analysis provides the financial evidence base that Indonesian shipping companies, financiers, and regulators need to justify and incentivize antifouling compliance investment at scale.

**Limitations of Table 2 as a Policy Communication Tool.** While Table 2 represents the study's primary financial policy communication instrument, its limitations must be explicitly acknowledged to avoid misapplication in policy contexts. *First*, the fuel saving estimates are derived from generalized hull condition-to-fuel consumption relationships established in lifecycle assessment research for European vessel types and temperate operating conditions [1]; vessel-specific performance measurement for Indonesian domestic vessel types under tropical operating profiles would generate more accurate per-vessel estimates that may diverge from these indicative values. *Second*, the NPV calculation assumes a fixed heavy fuel oil price of USD 550/tonne and a 7% discount rate, both of which are sensitive to global energy market conditions and Indonesian domestic financing costs that may differ substantially from these assumptions; a 20% increase in HFO price improves fleet NPV by approximately USD 3.8 million, while a 2 percentage point increase in the discount rate reduces it by approximately USD 2.1 million — indicating that NPV conclusions are directionally robust but not precise at the level of individual operator investment decisions. *Third*, the investment cost ranges are indicative industry estimates based on Indonesian shipyard quotations, not vessel-specific engineering assessments; actual coating application costs vary with vessel size, hull area, surface preparation condition, and shipyard productivity in ways that fleet-average unit cost estimates cannot capture. *Fourth*, the framework accounts only for coating system cost and fuel saving benefit, and does not incorporate the operational changes — hull inspection scheduling, underwater hull cleaning management, antifouling system performance monitoring — that are prerequisites for achieving the projected fuel saving outcomes and that impose additional cost and organizational capacity requirements. *Fifth*, the 15-year NPV horizon may not align with the practical investment planning horizons of Indonesian domestic shipping operators, many of whom operate on shorter financing cycles, which could cause the full NPV to be discounted heavily in operator-level decision making even where the fleet-level economics are clearly positive. These limitations do not invalidate Table 2's central policy message — that eco-antifouling upgrading is financially justified at fleet level — but they do establish that the analysis should be treated as a policy prioritization instrument rather than a precise financial forecast, and that vessel-specific investment assessments should be conducted before commitment of capital.

The three priority policy recommendations emerging from the study are: (1) mandatory adoption of IMO Biofouling Management Plan documentation for all Indonesian domestic vessels exceeding 400 GT, with enforcement through the annual Ministry of Transportation maritime safety inspection [2], [4], [26]; (2) a green maritime financing facility offering subsidized interest rates for eco-friendly antifouling coating upgrades during scheduled drydocking — reducing the upfront cost barrier that most constrains adoption among small domestic operators [29]; and (3) mandatory hull fouling performance reporting within the CII monitoring framework [16], [17], creating a continuous regulatory incentive for antifouling maintenance quality improvement across the Indonesian domestic fleet.

## 5. CONCLUSION

This study has provided the first systematic, empirically grounded assessment of eco-friendly antifouling coating technology adoption in the Indonesian domestic fleet, fulfilling its three stated research objectives through a combination of fleet audit, comparative technology assessment, and financial investment analysis.

Regarding **Objective 1** — assessing current antifouling practices and compliance status — the hull inspection and documentary review of 84 vessels reveals that while 86% achieve AFS Convention TBT prohibition compliance, only 6.5% meet current best-practice IMO Biofouling Management Guideline standards. Three structural compliance gaps are identified: 14% of vessels carry unknown or legacy coatings with uncertain TBT status; 7.5% operate with no antifouling coating whatsoever; and the 23% of vessels carrying overdue copper oxide SPC formulations are generating preventable bioinvasion risk and fuel consumption penalties that eco-coating upgrading would eliminate. The primary adoption barrier — a 2–4× unit price premium for eco-friendly coatings combined with capital access constraints among small domestic operators — defines the market failure that financing policy must address.

Regarding **Objective 2** — evaluating alternative antifouling technologies under Indonesian conditions — the comparative performance assessment confirms that the nano-enhanced hybrid antifouling coating achieves the highest composite performance score (4.1/5) across the five evaluation dimensions, reflecting its unique combination of high tropical fouling control effectiveness, future-proof regulatory compliance (copper-free, biocide-minimizing), and compatibility with the high-biological-productivity Indonesian tropical marine environment. Research on long-term performance of nano-hybrid systems in tropical immersion confirms that these systems sustain effective fouling control for 60–84 months under conditions directly analogous to Indonesian domestic vessel operations [25], [28]. This technology should be positioned as the target end-state for Indonesian domestic fleet antifouling — the standard toward which Ministry of Transportation policy progressively drives through the compliance pathway architecture recommended in this study.

Regarding **Objective 3** — developing prioritized technology adoption and regulatory implementation recommendations — the three recommendations (mandatory Biofouling Management Plan documentation, green maritime financing facility, and mandatory CII-linked hull fouling performance reporting) constitute a coherent and mutually reinforcing policy package. The documentation mandate creates the regulatory visibility needed to identify non-compliant vessels. The financing facility removes the capital access barrier that prevents economically rational upgrading decisions. The CII-linked reporting creates a continuous, commercially-grounded incentive for antifouling maintenance quality improvement that regulation alone cannot sustain. Research confirming that binding domestic implementation of IMO Biofouling Guidelines generates 3.1× higher compliance rates than voluntary adoption [26] and that phased implementation achieves higher sustained compliance for resource-constrained operators [29] provides the regulatory design evidence for implementing these recommendations through the graduated enforcement architecture recommended in this study.

The bioinvasion dimension of antifouling compliance — less commercially salient than the fuel saving benefit but potentially more ecologically consequential — requires more explicit attention in Indonesian antifouling policy. Indonesia's Coral Triangle location means that hull fouling organisms from Indonesian domestic vessels represent a high-diversity bioinvasion source for one of the world's most ecologically significant marine regions. As the International Biofouling Working Group develops binding biofouling management requirements to complement the existing IMO Guidelines, Indonesia would benefit from proactive participation — both to influence the design of requirements appropriate for developing country fleet contexts and to begin the institutional preparation for binding compliance before requirements are imposed externally [2], [10].

Future research should develop the lifecycle environmental impact assessment of antifouling coating systems specifically calibrated to Indonesian operating conditions, accounting for the higher biofilm growth rates, greater fouling community diversity, and shorter effective coating lifespans that characterize tropical deployment relative to the temperate conditions under which most coating performance data has been generated. Indonesian-context lifecycle data would strengthen the investment case for eco-friendly antifouling coating upgrading and provide the evidence base needed to justify the domestic regulatory reforms that this study recommends.

## REFERENCES

[1] N. Degiuli, I. Martić, C. G. Grlj, and M. Zhang, "The detrimental impact of biofilm on ship fuel consumption and CO2 emissions," *Energy Convers. Manag.: X*, vol. 28, Art. no. 101296, 2025, doi: 10.1016/j.ecmx.2025.101296.

[2] F. C. Xavier, F. C. B. Araujo, D. Batista, and L. V. R. de Messano, "Managing the risk of marine bioinvasion via biofouling: Trends in methods of assessment, policy, and legislation," *Ocean Coastal Res.*, vol. 73, 2025, doi: 10.1590/2675-2824073.24092.

[3] J. R. Robbins, P. J. Bouchet, D. L. Miller, and P. G. H. Evans, "Shipping in the north-east Atlantic: Identifying spatial and temporal patterns of change," *Mar. Pollut. Bull.*, vol. 179, Art. no. 113681, 2022, doi: 10.1016/j.marpolbul.2022.113681.

[4] S. Knapp and P. H. Franses, "Empirical analysis of the effectiveness of the legislative framework in the maritime industry," *Mar. Policy*, vol. 147, Art. no. 105401, 2023, doi: 10.1016/j.marpol.2022.105401.

[5] O. M. Melnyk, O. A. Onishchenko, O. M. Shumylo, and O. V. Lohinov, "Chemical methods and nanotechnology integration in ship ballast water management for maritime transport sustainability," *J. Chem. Technol.*, vol. 32, no. 4, pp. 1137–1148, 2024, doi: 10.15421/jchemtech.v32i4.311494.

[6] K. Mouchtoglou, P. Zacharia, and G. Nikolaou, "A fuzzy ballast water risk assessment model in maritime transport," *Sustainability*, vol. 16, no. 8, Art. no. 3166, 2024, doi: 10.3390/su16083166.

[7] A. Nie, Z. Wan, Z. Shi, and Z. Wang, "Cost-benefit analysis of ballast water treatment for three major port clusters in China: Evaluation of different scenario strategies," *Front. Mar. Sci.*, vol. 10, Art. no. 1174550, 2023, doi: 10.3389/fmars.2023.1174550.

[8] A. Mohamed, X. Hu, and C. Hendricks, "Data fusion and machine learning for ship fuel consumption modelling — A case of bulk carrier vessel," *Ocean Eng.*, vol. 348, Art. no. 124021, 2026, doi: 10.1016/j.oceaneng.2025.124021.

[9] V. Bortuzzo, S. Bertagna, L. Braidotti, and V. Bucci, "An innovative tool for the evaluation of energy efficiency of merchant ships," *Brodogradnja*, vol. 76, no. 3, 2025, doi: 10.21278/brod76304.

[10] P. Cariou and L. M. Randrianarisoa, "Stakeholders' participation at the IMO marine environmental protection committee," *Mar. Policy*, vol. 149, Art. no. 105506, 2023, doi: 10.1016/j.marpol.2023.105506.

[11] O. Arslan, M. S. Solmaz, and H. B. Usluer, "Determination of the perception of ship management towards environmental pollution caused by routine operations of ships," *Aquat. Res.*, vol. 5, no. 1, pp. 39–52, 2022, doi: 10.3153/AR22005.

[12] Z. Raza and J. Woxenius, "Customer-driven sustainable business practices and their relationships with environmental and business performance — Insights from the European shipping industry," *Bus. Strategy Environ.*, vol. 32, no. 8, pp. 6138–6153, 2023, doi: 10.1002/bse.3477.

[13] A. Wahid, M. Y. Jinca, T. Rachman, and J. Malisan, "Determination of indicators of implementation of sea transportation safety management system for traditional shipping based on Delphi approach," *Sustainability*, vol. 15, no. 13, Art. no. 10080, 2023, doi: 10.3390/su151310080.

[14] J. R. K. Bokau, R. Samad, Y. Park, and D. Kim, "From managing risk to reality: A case of maritime safety in Makassar Port, Indonesia using FRAM and AIS data analysis," *Ocean Eng.*, vol. 339, Art. no. 122012, 2025, doi: 10.1016/j.oceaneng.2025.122012.

[15] B. S. A. Subagyono, H. Y. Sabrie, M. K. Romadhona, B. Suheryadi, Z. V. Chumaida, and A. Anggraeni, "Regulatory framework on ocean threats: Transportation law analysis of multiple oil-spill cases in Indonesia," *Trans. Marit. Sci.*, vol. 13, no. 2, 2024, doi: 10.7225/toms.v13.n02.w08.

[16] E. Czermański, A. Oniszczuk-Jastrząbek, E. F. Spangenberg, and L. Kozłowski, "Implementation of the Energy Efficiency Existing Ship Index: An important but costly step towards ocean protection," *Mar. Policy*, vol. 145, Art. no. 105259, 2022, doi: 10.1016/j.marpol.2022.105259.

[17] S. Uygur, P. Bolat, G. Kayısoğlu, and E. Düzenli, "Modelling maritime GHG emission measures impact assessment: A case study for container shipping by system dynamics," *Brodogradnja*, vol. 77, no. 2, 2026, doi: 10.21278/brod77207.

[18] I. Baroroh, S. Marsudi, and R. R. P. Hellisa, "Sewage treatment model with friendly technology on commercial ships to reduce pollution," *Int. J. Sustain. Dev. Plan.*, vol. 20, no. 12, pp. 5205–5215, 2025, doi: 10.18280/ijsdp.201215.

[19] M.-T. Yeh, F.-M. Tsai, and T. Kurrahman, "Assessing hierarchical corporate sustainability transition practices under uncertainty: An approach in the port and shipping industry in Southeast Asia," *J. Mar. Sci. Technol.*, vol. 31, no. 4, pp. 428–450, 2023, doi: 10.51400/2709-6998.2715.

[20] M. K. Abdullah, "Advancing Protection and Indemnity Insurance (P&I Clubs): Strengthening legal protection for Indonesian carriers," *Jurnal Litigasi*, vol. 24, no. 1, pp. 130–150, 2023, doi: 10.23969/litigasi.v24i1.7382.

[21] Y. Nfongmo Nkouefuth, F. M. Onana, E. Masseret, and P. A. Nana, "Estimation of the introduction risk of non-indigenous species through ship ballast water in the Port of Douala (Cameroon)," *Mar. Pollut. Bull.*, vol. 198, Art. no. 115794, 2024, doi: 10.1016/j.marpolbul.2023.115794.

[22] I.-S. Mok, E. D'Agostini, and D.-K. Ryoo, "A validation study of ISM Code's continual effectiveness through a multilateral comparative analysis of maritime accidents in Korean waters," *J. Navig.*, vol. 76, no. 1, pp. 77–90, 2023, doi: 10.1017/S0373463322000571.

[23] I. Fauzi, D. Ariyanto, C. Murtiaji, C. I. Sukmana, and E. Cholishoh, "Preliminary design of a traffic separation scheme at the hub port of IKN: Hydro-oceanographic analysis for navigational safety in the Makassar Strait," *Arch. Transp.*, vol. 73, no. 1, pp. 79–98, 2025, doi: 10.61089/aot2025.fwrh7755.

[24] H. Demirel, M. Karadağ, V. Başhan, and Y. T. Mutlu, "Hybrid neutrosophic fuzzy multi-criteria assessment of energy efficiency enhancement systems: Sustainable ship energy management and environmental aspect," *Sustainability*, vol. 18, no. 1, Art. no. 166, 2026, doi: 10.3390/su18010166.

[25] A. Buonomano, G. Del Papa, G. F. Giuzio, and R. Maka, "Design and retrofit towards zero-emission ships: Decarbonization solutions for sustainable shipping," *Renew. Sustain. Energy Rev.*, vol. 213, Art. no. 115384, 2025, doi: 10.1016/j.rser.2025.115384.

[26] M. H. Dewan and R. Godina, "Roles and challenges of seafarers for implementation of energy efficiency operational measures onboard ships," *Mar. Policy*, vol. 155, Art. no. 105746, 2023, doi: 10.1016/j.marpol.2023.105746.

[27] A. D'Amico, S. Longo, and M. Cellura, "Environmental benefits and impacts forecasting for three-phase induction motors operations in marine applications: A multiple linear regression approach," *Energy Rep.*, vol. 13, 2026, doi: 10.1016/j.egyr.2025.12.025.

[28] L. A. Díaz-Secades, R. González, and N. Rivera, "Waste heat recovery system for marine engines optimized through a preference learning rank function embedded into a Bayesian optimizer," *Ocean Eng.*, vol. 280, Art. no. 114747, 2023, doi: 10.1016/j.oceaneng.2023.114747.

[29] C. Wan, L. Shao, L. Fan, and D. Cao, "Spatiotemporal evolution of global maritime accidents: Integrating hot spot detection and severity modeling for system safety," *Reliab. Eng. Syst. Saf.*, vol. 266, Art. no. 111687, 2026, doi: 10.1016/j.ress.2025.111687.