Environmental Sciences Europe

REVIEW

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Past, present and (possible) future of biofouling regulatory instruments within the international marine environmental protection framework

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Abstract

Marine biofouling is associated with remarkable impacts for many maritime industries and is linked with major environmental concerns. Although national biofouling regulations have been issued by a few countries in the recent past, these remain isolated initiatives. At a global scale, even if biofouling undeniably accounts for important costs and risks, there is currently no international legally binding framework on it. This work focuses on the evolution of international marine environmental protection legislation and analyzes existing regulatory instruments linked to the matter, with particular emphasis on the European legislation and other few regional in-force regulations on biofouling, and eventually focussing on the sector of recreational boating. Finally, the main gaps and challenges for the development of a regulatory framework on biofouling are identified and listed, along with the major learnings and proposals derived from the experimental outcomes of recent works, to provide an integrative tool for suitable antifouling selection.

Keywords Biofouling, Antifouling, Legislation, Guidelines, IMO, Integrative tool

Introduction

Any hard substrate exposed to or submerged in aquatic environments is susceptible to be colonised by organisms that compose the so-called hard-substrate communities, in a succession process that goes from a biochemical conditioning and biofilm formation to more mature, three-dimensionally complex communities [95]. The specific case of unwanted settlement and growth of organisms on artificial hard substrates partially or totally exposed to aquatic environments is referred to as biofouling [65].

The development of fouling communities is a fast, dynamic and cumulative process that can pose several problems for many human activities in sectors, such as aquaculture, extractive industry, renewable energy production and its transportation, monitoring systems, maritime defence and transport, tourism, and other forms of navigation ([4, 39, 88, 122], 6). Therefore, it is considered a cross-sectorial issue relevant within the blue economy. Its development is associated with remarkable impacts for the involved industries and is linked with major environmental concerns.

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Marine biofouling in numbers: economic costs

Biofouling is a global and cross-sectorial issue that accounts for millions of euros annually. If we focus on maintenance derived expenses, at a time, an early study estimated that US Navy costs tied to biofouling for hull cleaning, paint removal and repainting, toxic water and grit disposal, OSHA health requirements, labour associated with corrective measures, and other maintenance measures were approximately 100–200 million US$ a year [1]. More recently, for the fishing fleet of Cantabria (Spain), the economic impact estimation resulted to be approximately the 3% of the intermediate consumption of the ship with respect to its fish production, and almost 40% of the costs for spare parts, repair, and maintenance of the ship [124]. The authors calculated the total average annual costs of maintenance of the underwater hull to be 9,220 € per ship and 1,244,700 € for the total Cantabrian fishing fleet. In oil and gas industry, the cost to manually clean these platforms of accumulated organisms is approximately 30,000–100,000 US$ per cleaning cycle [87]. The amount increases remarkably when the platforms reach their final stage and need to be decommissioned, with cost estimates ranging from 50,000 US$ for the smallest platforms to over 100 million US$ [80, 87]. Finally, although it is difficult to determine the exact cost associated to biofouling in the aquaculture sector, estimates indicate that between 5 and 10% in industry value is spent in dealing with fouling related issues every year. This typically accounts for 20–30% of total operating costs and can be translated in 260 million € annually only for Europe [38, 64]. Taking as an example the sector of marine salmon aquaculture, the cost per farm site and production cycle ranged between 420,000 and 493,600 US$ [8]

Additional costs on fuel consumption, which are directly related with fouling development and surface roughness, can be included in the equation in cases of mobile elements such as vessels. According to the study by [105], heavy slime, considered a level typical of the representative vessel DDG-51 of the US Navy, can increase fuel consumption by 10.3% and fuel costs by approximately 1.15 M US$ per ship per year. Similarly, the IMO calculated an increase in 25% of fuel consumption and greenhouse gases emissions in a bulk carrier with 0.5 mm-thick biofilm covering 50% of the submerged surface (GEF-UNDP-IMO GloFouling Partnerships Project & GIA for Marine Biosafety, [43]).

Shipping has been identified as the main anthropogenic pathway, i.e., mean, for the entry or spread of species outside their natural range, namely, non-indigenous species (NIS) [74]. Biofouling is also globally recognised as a major vector for the introduction of non-indigenous aquatic species [18, 51, 100], along with ballast water, although this later one is currently regulated [18]. The introduction of NIS, in particular invasive alien species (IAS, see [113] for differences in terminology), is another major economic concern, as it can account for remarkable costs derived from direct and indirect impacts of the introduced species. Efforts are now being done to integrate direct measurable costs and quantify ecological losses. Globally, cumulated costs linked to aquatic invasive alien species accounted for 345 billion US$ based on 5682 records from the expanded InvaCost database, with an observable increase in various orders of magnitude over the last years [24].

Marine biofouling in numbers: ecological costs

Biofouling poses important environmental and biosecurity risks related to the introduction and spread of NIS. The translocation of organisms outside their natural range is considered one of the main threats for global biodiversity. In particular, the introduction of NIS poses a risk to the intrinsic value of biodiversity itself, with further effects on ecosystem services [17] and biosecurity, whose impacts can go as far as pathogen translocation, and public and domestic or farmed animal health concerns [46].

A report by Scianni et al. [106] gathered and updated global marine NIS introductions, hereby summarised for the purpose of illustrating in numbers the impacts of biofouling as a NIS vector. According to it, tidal waters of North America host 450 established marine and estuarine NIS, of which 44–78% are attributable to shipping, either by ballast water or by biofouling. Other regional estimates, also mentioned in the report, indicate that biofouling is responsible of up to 58% of the established coastal and estuarine NIS invertebrates and algae in Puget Sound in Washington State [27], 60% in California [101] and 78% in Hawaii [28]. As for the Mediterranean Sea, aside of embracing the largest number of species for its size on the planet [19], it also hosts the highest know number of NIS in the world, with estimates pointing out to nearly 1000 species, most of which arrived through the Suez Canal [140]. In this particular context, biofouling of recreational boats has been repeatedly suggested as major vector for the secondary spread of NIS, offering frequent opportunities for transfers and high connectivity between locations ([126], Ashton et al., 2022).

Scope of the work

Biofouling clearly poses important losses, both at economic and ecological levels. To prevent or minimise its development and associated impacts, antifouling measures and management strategies are applied [26, 27, 52]. However, the regulatory framework directly addressing it is scarce and very scattered. The current legislation unequally addresses different sectors, leaving some of these completely neglected. It is of particular concern the case of recreational boating, lacking of regulatory and enforcement tools that allow a solid legislative and implementation framework, in spite of the importance of this sector.

Despite biofouling of recreational boats being the main focus of this work, at the light of today's global legislative scenario, which lacks a specific regulatory instrument on the matter, this work: (1) reviews the evolution of international environmental protection, with particular focus on EU context and other regional cases, (2) analyses the current regulations related to biofouling and its control, and (3) provides evidences and learnings, intended as proposals addressing identified gaps, aiming for their integration in existing biofouling management plans, mainly for the recreational boating sector, which could ultimately lead to a comprehensive biofouling policy framework.

Methodological approach

Traditional methods for systematic review were not fully applicable to this work; therefore, we used a top–down approach instead. Comprehensive textbooks on environmental legislation [48, 118], and dedicated web portals (EUR-Lex European Union law portal, IMO ePublications and media centre; ECOLEX; UNEP Publications & Data portal) were used as a baseline for the extraction of major sources and as a starting point for searches or more specific provisions and regulations. Other domestic regulations on the matter were accessed through their respective official portals (as specified accordingly in the references). Finally, to complement the interpretation of existing legislative instruments and support statements and recommendations, relevant scientific literature was consulted.

Addressing marine environmental threats derived from shipping

The global nature of shipping industry and the motile essence of boats of all classes implies that vessel derived marine pollution needfully requires to be dealt at international level. Threats and risks associated with shipping are rather broad; however, we will focus on the usage of antifouling systems and the environmental risks of biofouling itself. Still, a summary of the international regulatory instruments is herewith considered fundamental, mostly sourced from Harrison [48] and Tanaka [118]. A supportive chart (Fig. 1) was additionally created with the purpose of accompanying the text explanations on the chronological development of the discussed regulatory instruments.

International regulatory framework

Understanding and beating marine pollution is acknowledged as the first out of ten challenges of the United Nations Decade of Ocean Science for Sustainable Development [49]. Globally, the most important legal instrument in the modern law of the sea relies in the United Nations Convention on the Law of the Sea, adopted in 1982 (UNCLOS, [129]), a convention whose origin dates back to 1958 with the first United Nations Conference on the Law of the Sea, leading to important international treaties. However, imbalanced rights and obligations, an overall sense of dissatisfaction in the international community, together with catastrophic events (*Torrey Canyon* incident in 1967), evidenced a deficient marine environmental protection and an urgent need to address environmental emergencies, whilst promoting preventive and protective measures on its regard. Without a designated body with specific competences on the matter (back then, the International Maritime Organisation (IMO) only worked as a forum for cooperation on shipping regulation), a new gathering was set to discuss existing deficiencies in UNCLOS I (1958) and demand a regulatory body with competences. Finally, the question of marine pollution was raised at the *United Nations Conference on the Human Environment* [128], which concluded with the *Stockholm Declaration and Action Plan for the Human Environment* (Fig. 1), setting the starting line in marine environmental protection [128]. It all propelled a series of changes, including the creation of the United Nations Environment Programme (UNEP, [128]), the broadening of the IMO competences in 1975 and the establishment of a permanent Marine Environmental Protection Committee (MEPC) (IMO Convention, after the amendments of 1975), as well as the convening of the third and last United Nations Conference on the Law of the Seas in 1973 and the negotiations for provisions on the protection and preservation of the marine environment, integrated in the final UNCLOS text as Part XII of the Convention, adopted in 1982 [129] (Fig. 1).

Still, first steps on environmental protection had started earlier in time, but specifically addressing vessel-sourced oil pollution of the marine environment, the *1954 International Convention on Pollution of Sea by Oil* (1954 OILPOL Convention) (Fig. 1) [48, 127]. This treaty was soon considered deficient in many aspects, falling to cover other types of pollution from the same source.

The 1954 OILPOL Convention cleared the way to the *International Convention on the Prevention of Pollution from Ships* (MARPOL Convention, 1973), as amended by the adoption of a Protocol in 1978, and still today, is the major treaty to regulate marine pollution sourced from ships, with 161 parties to it, making it 99.89% of the gross tonnage of the world's merchant fleet [56] (Fig. 1).

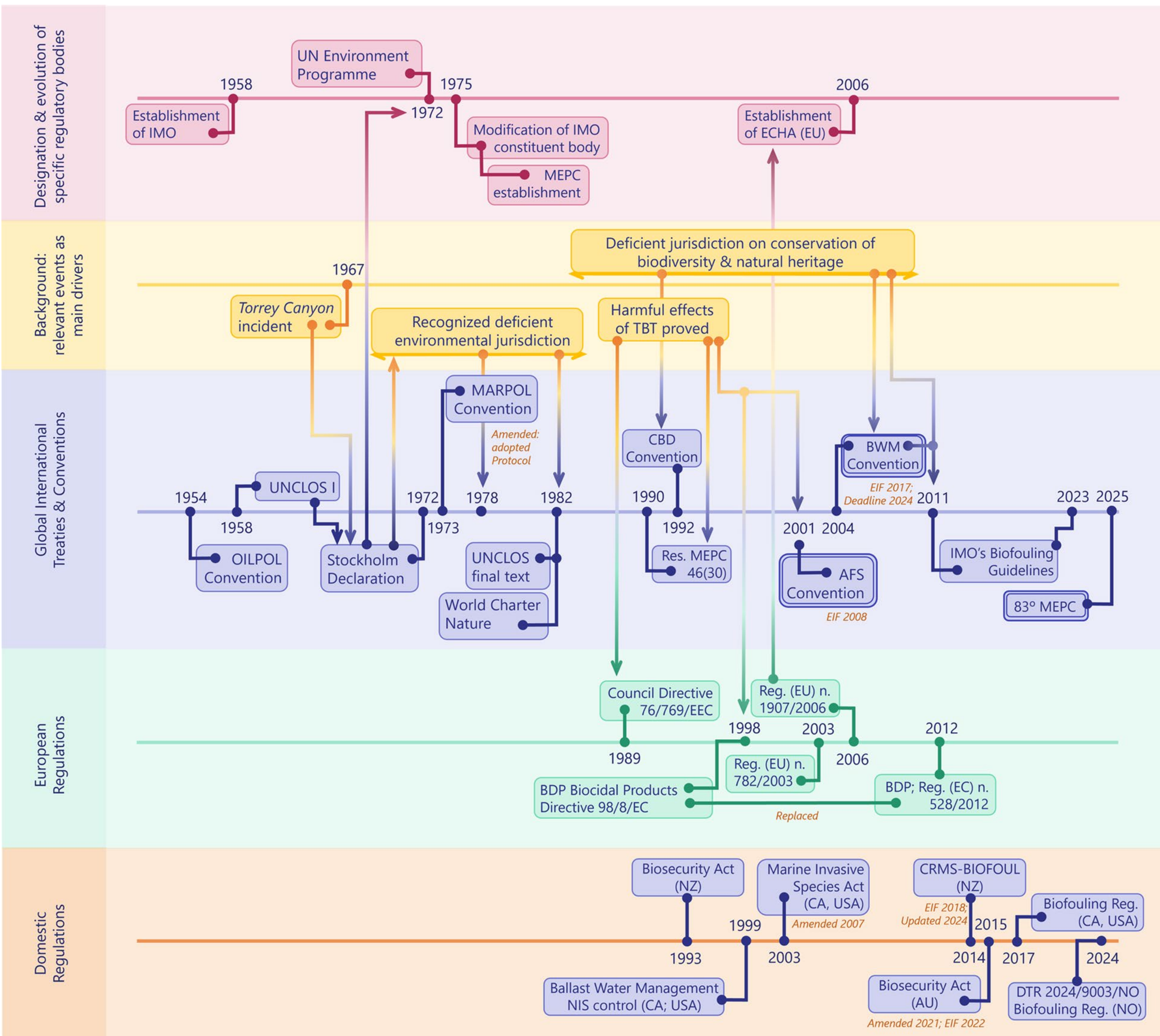

Fig. 1 Chronological development of the major regulatory instruments, including those relevant for biofouling management, divided into colour coded sections. From up to bottom: section "Introduction" (pink): designation and evolution of specific regulatory bodies; section "Addressing marine environmental threats derived from shipping" (yellow): relevant events and main drivers; section "Current policies and legislation on antifouling systems" (blue): global international treaties and conventions; 4 (green): European regulations; 5 (orange): domestic regulations. The historical background is provided to contextualise the convening of international meetings, the creation of competent bodies, and the development of regulatory instruments and their amendments or substitutions. The interactions are indicated with an arrow (effect arrow), pointing the direction of the effect and colour coded indicating the transition between sections. Doubled blue box margins in the section of global international treaties and conventions indicate major IMO milestones. EIF: Entry In Force

It classifies vessel-sourced pollution addresses particular them in designated annexes, providing detailed technical standards [118]. At smaller scale, specific directives on environmental protection aim to set quality standards and mechanisms to achieve those. In particular, in EU, the Water Framework Directive (WFD, [35]/60/EC) "set out rules to halt deterioration in the status of EU water bodies and achieve good status for Europe's waterbodies, including coasts, rivers, lakes, and groundwater", and fuelled specific daughter directives like the Marine Strategy Framework Directive (MSFD, [36]/56/EC). Other efforts at smaller scale have also been taken, including multiple regional conventions [47, 48, 85]. The definitions and provisions of these treaties and conventions are of broad scope, thought in such a way to be applicable to all sources of pollution, making them flexible enough to face new environmental threats as they emerge, backing-up specific regulatory instruments thereafter developed.

Current policies and legislation on antifouling systems

Background: understanding the origins of antifouling systems' regulations

Regulations on antifouling systems saw light after undeniable evidences of serious environmental impacts derived from the use of tributyltin-based (TBT) paints. In the 1960s, the usage of TBT containing paints was very much spread due to their high efficiency related to its toxicity. Yet, the effects were observable beyond target species, with impacts in the surrounding environments and the species they host. These effects included imposex in gastropods and consequent reduction in reproductive capability; shell deformation and abnormalities in oysters; as well as bioaccumulation potential and persistence in sediments [10, 94, 102, 115]. Gradually, supported by the scientific evidence, restrictions on its use arrived (Council Directive 76/769/EEC, 1989,MPEC Resolution 46(30), 1990), leading eventually to its global ban in 2001 with the adoption of the *International Convention on the Control of Harmful Anti-fouling Systems on Ships* (AFS Convention, [53]) and the European Union (EU) Regulation (EC) No 782/2003, aiming for its effective elimination from ships by 2008 (Fig. 1).

International level

The AFS Convention emerges from the decision to develop a self-standing treaty, rather than a new Annex to MARPOL Convention, based on practicalities [48]. The AFS Convention also introduces the important obligation to the parties of "taking appropriate measures to promote and facilitate scientific and technical research on the effects of antifouling systems as well as monitoring such effects", permitting the proposal of antifouling systems to the Annex 1 of the Convention, which lists prohibited antifouling (AF) systems. To this end, the Convention sets a group of technical experts to review proposals and report decisions to the Committee, which dictates the final resolution applying the precautionary approach [Article 6(3)].

European level

At European level, the Regulation (EC) No 1907/2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) establishes a general framework for the legislation of substances "ensur[ing] a high level of protection of human health and the environment as well as the free movement of substances, (…), whilst enhancing competitiveness and innovation" (Art. 1). In this aim, it establishes the European Chemicals Agency (ECHA), an independent central entity for the effective management of the technical, scientific, and administrative aspects of this regulation (Fig. 1).

Specific regulations concerning biocides in particular were first gathered under the Biocidal Products Directive (BDP; Directive 98/8/EC) and later on replaced by the Regulation (EC) No 528/2012. These provisions regulate the usage of biocidal products and the authorisation for placing them on the market, including biocides as antifouling agents (product type 21), always ensuring that "they are sufficiently effective and have no unacceptable effect on the target organisms such as resistance, or, in the case of vertebrates, unnecessary suffering and pain. Furthermore, they may not have, in the light of current scientific and technical knowledge, any unacceptable effect on human health, animal health or on the environment. Where appropriate, maximum residue limits for food and feed should be established with respect to active substances contained in a biocidal product to protect human and animal health" (Article 19 1(b)) (Regulation (EU) No 528/2012).

Currently, unauthorised biocidal antifouling products banned from use include TBT [53, 96]; Regulation (EC) 536/2008) and Irgarol (cybutryne) (MEPC 76/3/7 (69); Commission Implementing Decision (EU) 2016/107, [20]), both listed under the Annex I of the AFS Convention, although some studies keep reporting the use and commercialization of the first one [90, 125].

Other domestic regulations

At national level, domestic regulations can extend the limit of usage to additional substances and, therefore, the list of unauthorised substances can differ across countries [94, 120]. Copper is still widely used, cuprous oxide being the main active agent used in the market [2, 57, 138]. Nonetheless, increasing concerns regarding its environmental impacts have made copper go under scrutiny [2, 26, 86, 114, 138]. Consequently, some countries are starting to limit its use and/or concentration as biocide in AF coatings, including the Danish Environmental Protection Agency ([31; [33]) in the Baltic region, as well as certain US states like California (California Regional Water Quality Control Board for San Diego Region, [14]; and Los Angeles Region, 2015) and Washington (Washington State Legislature, [133]). Additionally, the United States Environmental Protection Agency (US EPA) is also promoting the shift towards safer alternatives that exclude the use of copper by financing projects such as the one in San Diego bay ('Copper Reduction Program', [93]) and is currently working on a 'Clean Boating Act' (US [131]).

Surprisingly, in Europe, despite having specific directives that address the issue of marine environmental status, with tailored assessments designed for its monitoring, the reporting of certain substances is regarded as voluntary. As an example, the Baltic Marine Environment Protection Commission (Helsinki Commission, HELCOM) considers reporting copper concentrations voluntary, limiting mandatory metal indicators to just three, these being mercury, cadmium, and lead [50]. Proposals to have copper included as a core indicator in HELCOM third Holistic Assessment (HOLAS III) have been raised [62], together with the load compilations from shipping and leisure boats [139], after it being identified as a remarkable source of pollution linked with AF usage [37, 139].

Current policies and legislation on biofouling

Thus far, it has been addressed the legislation on the usage of certain chemical substances, including also the case of biocides in antifouling paint formulations. These regulations focussed on the chemical aspect of biofouling control, aiming for environmental protection and pollution prevention. Therefore, their focal point is the assessment of chemical risk and limitation, when applicable, of certain substances to safeguard marine environmental health. However, even if they relate to the issue of biofouling, they do not state the need of controlling biofouling nor provide measures to do so. In fact, to date, there is no international legally binding framework on biofouling, which, despite being associated with important costs and risks, at a global scale, remains largely unregulated, although a few remarkable exceptions exist (Fig. 1; Table 1), as discussed below.

Voluntary management of biofouling is a common practise, yet it focuses on drag reduction, fuel saving, and the cost and effectiveness of the biofouling control method, but without specifically targeting the biodiversity conservation goals. As a result, it only partially addresses the NIS introduction problem, and some commonly employed antifouling practises, such as in-water cleaning, may be ineffective for certain taxa [41] or may even result in dissemination of biofouling propagules and promotion of new NIS introductions [117]. The need for an international regulatory framework on biofouling is strictly linked to the conservation of biodiversity and the concept of biosecurity. Although the Stockholm Declaration states that "[hu]man has a special responsibility to safeguard and wisely manage the heritage of wildlife and its habitats (…)" [128], the concept of biodiversity in international rules emerged a decade later with the World Charter for Nature [134], as a non-binding instrument adopted by the UN General Assembly. The first global binding treaty on biodiversity arrived in 1992 with the Convention on Biological Diversity [130] (Fig. 1). The CBD Convention established a general framework for the conservation of biological diversity and sustainable use of its components, demanding the integration of biodiversity conservation into (cross) sectorial plans, programmes and policies (Art. 6 and 10), as well as the implementation of environmental impact assessment plans for individual projects. Particular measures to ensure in situ conservation are stated in the Article 8, in which, "each Contracting Party shall, as far as possible and as appropriate (…) prevent the introduction of, control or eradicate those alien species which threaten ecosystems, habitats or species". However, the CBD itself does not perform a regulatory role and acts as an umbrella treaty, in which the Parties, ultimately, are to take further action to regulate activities.

Under the umbrella of the CBD, more regulations are still needed, as the international legal framework on biological diversity and its conservation is of a broad scope. Efforts to tackle biodiversity loss include the prevention of biological introductions, through instruments such as the Regulation (EU) No 1143/[98] of the European Parliament and of the Council on the prevention and management of the introduction and spread of invasive alien species at European level (recently modified through the Commission Implementing Regulation (EU) 2024/574 in February 2024) or New Zealand's Biosecurity Act [83]. Their application to the marine environment, however, is particularly challenging because of the complex jurisdictional regime governing it, as well as the intrinsic difficulties to study it and the greater scientific uncertainty surrounding certain marine ecosystems [48].

IMO guidelines

As stated above, the Art. 8 of the CBD (UNEP, 1992) states the obligation of targeting alien species and their vectors of introduction, but the nature of the issue implies that only international regulations can effectively address the problem.

The IMO has, during the last two decades, addressed the issue of NIS introduction related to shipping, first with the Ballast Water Management (BWM) Convention in 2004 as a binding instrument, and after with voluntary guidelines focussed on biofouling as the vector of introductions. The case of BWM Convention is herewith considered of particular interest, acting as a reference paving the way to a potential future international regulation of biofouling. During the 1980s, after the initial steps on the protection of the marine environment (focussed on pollution), increasing concerns on biological diversity were emerging, including those related to marine alien species. As mentioned above, a series of events (WCN; CBD Convention) succeeded, and the IMO took steps forward to address the issue. In 1993, the IMO finally adopted the *Guidelines for Preventing the Introduction of Unwanted Aquatic Organisms and Pathogens from Ships'*

Table 1 Summary of existing domestic regulations on biofouling

Regulation	Geographical range	Date	Vessel type(s)	Enforcement mechanisms	Penalties	Reference
California Biofouling Regulations	*State of California, USA*	2017	≥ 300 gross registered tonnes	Require Biofouling Management Plan (BFMP), Biofouling Record Book (BFRB) and 'Annual Vessel Reporting Form'	60-day grace period, otherwise Notice of Violation	California State Lands Commission
Craft Risk Management Standard (CRMS) for Vessels	*New Zealand*	2014; EIF 2018; updated 2023	All vessel types	Requirement to provide evidence of biofouling management 48 h prior to arrival, supports IMO tools (BFMP; BFRB) Hull inspections Working on "Approved Biosecurity Treatments" (MPI-STD-ABTRT)	Restriction of the itinerary in New Zealand; restrict the entry of the vessel into New Zealand territory; require management actions to enter	Ministry of Primary Industries [77]
Australian Biofouling Management Requirements	*Australia*	2015; EIF 2022; updated 2023	Compulsory declaration for commercial vessels; optional for non-commercial vessels	Vessel pre-arrival report 12–96 h prior to arrival declaring compliance to: a) implementation of BFMP; BFRB, or b) biofouling management in the last 30 days, or c) any other pre-approved alternative management method Verification upon arrival (inspections)	When unable to demonstrate requirements, further actions can be taken by authorities	Department of Agriculture, Fisheries and Forestry [25]
DTR 2024/9003/NO	*Norway*	2024; expected EIF 2025	Certain vessels types (cargo, passenger, and fishing vessels with trade area Bank Fishing I or greater trade area); 'mobile offshore units'	Requirement of BFMP and BFRB; obligation of implementing a biofouling control and management system Vessel inspections		Norwegian Maritime Authority [81]

Ballast Water and Sediment Discharges, a non-binding instrument giving guidance to States on measures to be taken on the matter. Further efforts first leaned into the creation of a new Annex to MARPOL Convention, but eventually, in 1997, the IMO decided to work towards a self-standing treaty, which saw light in 2004, and entered in force only in 2017, but with a time frame of 7 years for parties to implement it within National Regulations (deadline in 2024). The BWM Convention includes measures to be taken by both coastal and flag States and sets regulations for ballast water management, according to vessel dimension and construction date. Ships built after certain date are required to have approved ballast water management systems that ensure the treatment of these waters on board (BWM Convention, Regulation D-3; [54], and to date, these systems include more than a hundred [55]. It also states the requirement of a record book containing all the ballast water operations, including reasons of discharge. It establishes regulations and minimum standards for ballast water management, but recognising the right of the coastal States to take 'more stringent measures' on the matter (BWM Convention [54], Art. 2(3)) and encourages them to implement continuous monitoring (Art. 6). Finally, the Convention sets the obligation of providing technical assistance for developing countries to support them with all the duties. In particular, the IMO, together with other partners, does so under the umbrella of a specific programme (GEF-UNDP-IMO GloBallast Partnership Project).

Regarding biofouling management, coordinated international efforts to address it started in 2006, after formally raising the matter at the IMO [107], which was placed on the agenda of the MEPC in 2007, leading to the establishment of an IMO correspondence group on biofouling the year after [45]. The first voluntary *Guidelines for the Control and Management of Ships' Biofouling to Minimize the Transfer of Invasive Aquatic Species* arrived in 2011 [70] and were extended to leisure boats with the *Guidance for Minimizing the Transfer of Invasive Aquatic Species as Biofouling (Hull Fouling) for Recreational Craft* [71]. These guidelines have been updated (MEPC, 2023b) after the launch of a global project on the topic (GEF-UNDP-IMO GloFouling Partnerships Project). These guidelines propose the development and application of two vessel-specific tools: the Biofouling Management Plan (BFMP) and the Biofouling Record Book (BFRB), mirroring the steps taken for the BWM Convention.

To date, these are the only international documents that set a baseline for biofouling control, although their provisions remain voluntary. The complexity of the issue of biofouling, characterised by clear challenges (see below), lessens the pace of the regulatory process. Still, exemplary cases with enforced legislation on the matter exist and are the proof that biofouling regulation, albeit tricky, is an achievable goal and a necessary process.

California biofouling regulations, State of California, USA

California launched a programme for the control of NIS though ballast water in 1999 and Marine Invasive Species Act followed in 2003. Based on scientific evidence and existing data on vessel maintenance, operational practises and biofouling surveys, California's Legislature amended the Marine Invasive Species Act of the state in 2007, which addressed ballast water but not biofouling itself; placing a mandate on the California State Lands Commission (CSLC) with the aim of developing and adopting regulations on biofouling management [12, 107]. The CSLC started working on specific regulations in 2010, supported by an advisory technical group, which finally arrived in 2017 as California Biofouling Regulations (California State Lands Commission, [15]). The process was accompanied of stakeholder engagement, outreach campaigns, industry meetings, etc. before the entry into force in October of the same year. However, these provisions apply only to large vessels (vessels 300 Gross Registered Tonnes or above) that "carry, or are capable of carrying, ballast water that arrive at a California port". Similar to what proposed by the IMO guidelines, these vessels require having a BFMP and BFRB as well as submitting an 'Annual Vessel Reporting Form'. If vessels are found to violate those requirements during an inspection, 60-day grace period is given to correct the deficiencies that, once over, if these prevail, the vessel will receive a Notice of Violation.

Craft risk management standard for biofouling on vessels arriving to New Zealand, New Zealand

By the time that the CBD entered into force in 1993, New Zealand was launching a legislative tool to protect their local biodiversity, addressing the issue of *pests*. The Biosecurity Act of 1993 is an "act to restate and reform the law relating to the exclusion, eradication, and effective management of pests and unwanted organisms" which are defined as "any organism that a chief technical officer believes is capable or potentially capable of causing unwanted harm to any natural and physical resources or human health" (Biosecurity Act; New Zealand Legislation, [83]). It provided the background for the development of further regulations addressing specific vectors. In particular, a targeted research and risk analysis period between 2004 and 2007 led New Zealand to identify biofouling-related NIS introduction as a key priority for the country's biosecurity [107]. A consultation was launched on biosecurity management [45] and translated into a consultation paper [75], followed by further research and cost–benefit analysis [9], and ultimately culminating with the development of *Craft Risk Management Standard for Biofouling on Vessels Arriving to New Zealand* (CRMS-BIOFOUL) by the Ministry for Primary Industries (MPI) in 2014 and adopted that same year. The entry in force considered a 4-year adaptation period in which compliance was voluntary. In 2018, it finally became of mandatory implementation [76], in this case, for all vessel types, including recreational boats. Recently, the CRMS-BIOFOUL has been updated into the *Craft Risk Management Standard* (CRMS) *for Vessels* [77].

The MPI regards that "marine pests and diseases introduced to New Zealand on vessel hulls (biofouling) are a threat to our marine environment and resources. All vessels arriving in New Zealand must provide evidence of biofouling management prior to arrival". Therefore, vessel operators or the person in charge is required to take preventive biofouling measures prior to the arrival to New Zealand territory (excluding innocent or transit passage) and sets a minimum outcome to be met. In particular, the person in charge shall provide, at least 48 h prior to the vessel's entry into New Zealand territory, the MPI with (1) vessel details, (2) voyage details, and (3) biofouling information, as stated in the section "Methodological approach" of the CRMS for vessels [77]. The CRMS relies on IMO guidelines as a model of good practises and, currently, the MPI is working on a document with the "Approved Biosecurity Treatments" (MPI-STD-ABTRT). In case of noncompliance, the MPI may (a) require a hull inspection upon arrival to New Zealand territory, (b) restrict the itinerary in New Zealand; (c) restrict the entry of the vessel into New Zealand territory; or (d) ask for vessel cleaning within 24 h by an approved provider in New Zealand, all at the expense of the vessel owner or operator. To ensure compliance with the CRMS for vessels, the MPI has a fully dedicated site [78] with all the required information, complemented with additional resources and tools that facilitate boat owners [79] and operators to prepare their entrance in New Zealand territory.

The Australian biofouling management requirements, Australia

The Biosecurity Act of 2015 is an "Act relating to diseases and pests that may cause harm to human, animal or plant health or the environment" [84]. In 2021, a Regulation Impact Assessment was carried out, aiming to provide policy options to improve the regulation of biosecurity risk associated with biofouling on vessels arriving into Australian territory. The decision was to rely on proactive biofouling management practises. The Biosecurity Act 2015 was amended in 2021 (*Biosecurity Amendment (Biofouling Management) Regulations 2021*) and in force since 2022. The Department of Agriculture, Fisheries and Forestry (DAFF), in charge of its administration, implemented an 18-month education phase after extensive consultation with stakeholders.

The *Australian Biofouling Management Requirements* [25], in particular, "set[s] out vessel operator obligations for the management of biofouling when operating vessels under biosecurity control within Australian territorial seas. These requirements apply to all operators of vessels subject to biosecurity control and provide guidance for vessel operators on best practise biofouling management". It established the requirement of submitting a vessel pre-arrival report for commercial vessels through the department's Maritime and Aircraft Reporting System (MARS) at least 12 h prior to its entrance in Australian territory and not before 96 h. Vessel operators shall report compliance with one of the established options of biofouling management: (a) implementation of an effective BFMP and BFRB (as in IMO guidelines); (b) cleaning of all biofouling within 30 days prior to the arrival; or (c) implementation of an alternative biofouling management method pre-approved by the DAFF. Vessel operators that cannot demonstrate compliance with one of the three proactive biofouling management options will be subject to further pre-arrival reporting questions through MARS [25]. MARS is therefore used by the DAFF as a tool to target vessel interventions and assess biosecurity risks associated with vessel biofouling. Finally, verification upon arrival is carried out to certify compliance with the stated requirements. Reporting for non-commercial vessels is regarded as optional, through a non-commercial vessel pre-arrival report.

Regulations on the management of hull biofouling, Norway

The case of Norway can be considered the most recent step forward by a State to regulate biofouling (DTR 2024/9003/NO), led by the Norwegian Maritime Authority [81], following IMO guidelines for the control and management of ships' biofouling. The aim of the regulation is "to prevent the introduction of hazardous invasive species to Norway through hull biofouling resulting from international shipping, and to prevent the further spread of hazardous non-indigenous species in Norwegian waters" (Section "Introduction"). Just like in California State, these provisions apply only to certain vessels types and '*mobile offshore units*'. Specifically, it applies to "Norwegian passenger ships, cargo ships and barges certified for foreign voyages, as well as for mobile offshore units and for fishing vessels with trade area Bank Fishing I or greater trade area when they are in Norwegian territorial waters, (…), in Norwegian [EEZ] and on Norwegian Continental Shelf" (Section "Addressing marine environmental threats derived from shipping"). However, they share with other regulations the requirement of BFMP and BFRB, as well as the obligation of implementing a biofouling control and management system. Additionally, they provide an alternative option to the BFMP and to the control system and state the conduction of inspections as independent assessments and entry requirements.

A first regulatory document was drafted and notified to the EU Commission in March 2024, which was in standstill until June, when no conflict with the community regulations was found [123]. Although its entry into force was initially planned for 2024, the consultation period between March and June provided feedback and information that resulted in the decision of reassessing initial regulation draft and incorporate changes [82]. Currently, its entry into force is expected by July 2025 [81].

Implementation and enforcement: from adoption to action

Generally, the implementation and enforcement of international shipping standards relies on three main jurisdictional mechanisms: (1) the flag State jurisdiction, (2) the coastal State jurisdiction, and (3) the port State enforcement jurisdiction.

Flag States have primary responsibility to implement international standards and national regulations, it being a basic principle of the law of the sea that flag States have jurisdiction over their ships for all matters, regardless where they are in the world (UNCLOS, Art. 94; [129]). Flag States bear due diligence obligation to take all appropriate measures to prevent violations of regulations and shall do so by instruments, such as inspections and certifications, as well as investigations of suspected violations. To ensure implementation of standards by the States, external mechanisms have been approved by the IMO in 2005 and relate to audit schemes (a Member State Audit Scheme) and specific sub-committees (Flag State Implementation Sub-Committee) [48].

Coastal States have an important role in prescribing and enforcing international standards in the areas in close proximity to their coast, yet, these may depend on the location of the vessel (territorial waters or exclusive economic zone, EEZ) and the type of standard. In the territorial sea, the coastal State is given the power to enforce its own laws and regulations (UNCLOS, Art. 220; [129]), but mostly limited to discharge and operational standards and protection of particular ecological features, always ensuring the right of innocent passage, and shall do so by taking special navigational measures, e.g., prescribing sea-lanes or traffic separation schemes. In the EEZ, the coastal State's power is additionally limited and dependant on the degree of harm or threat to the marine environment (UNCLOS, Art. 220 [129]). The adoption of navigational measures in this area needs the approval of a competent international organisation (UNCLOS, Art. 211(6) [129]), and further interventions (inspections and judicial proceedings) need to be backed up by evidence of violation.

Port State enforcement jurisdiction refers to the situation in which action is taken against a vessel for a violation of international or national standards, including those that have taken place at sea before entering the port, with UNCLOS considering three main scenarios:

1. Enforcement of quasi-territorial jurisdiction [48, 73], or 'effects jurisdiction' when a vessel is voluntarily in port and suspected of violation of standards
2. Proceedings against a vessel or gathering evidence of noncompliance on behalf of another State (coastal or flag State) (MARPOL Convention, Art. 6(5)).
3. Enforcement of so-called 'universal jurisdiction' [7, 48] on behalf of the international community regarding violations of applicable international rules and standards in high seas (UNCLOS, Art. 218 [129]).

Although not explicitly mentioned in the Convention, a port State shall also set and enforce standards or conditions that must be met by a vessel to enter the port, considered a matter of general international law [48]. A port State can do so by denying access to its ports, regarded as an exercise of sovereignty, or by sanctioning any violation (lack of information regarding the voyage, false information, etc.). Mechanisms, such as the Paris Memorandum of Understanding (Paris MoU) on Port State Control and several other regional MoUs, allow harmonised PSC. Further collaborations between the Paris MoU and the its counterpart Tokyo MoU have given rise to Concentrated Inspection Campaign on BWM enforcement (Paris [89]).

Recent examples of port State enforcement jurisdiction on the matter of national biosecurity include multiple cruises (Viking Orion, the Coral Princess, the Seven Seas Explorer, and the Queen Elisabeth) that were denied entry permission in New Zealand and Australian ports [67, 119]. These port authorities, by routinely inspecting vessels on biofouling level, even domestic ones, [44], can detect cases of incompliance and take measures on the matter, including the entry denial until appropriate actions (e.g., cleaning) are taken.

Gaps and challenges

A complex panorama lies ahead regarding the issue of biofouling, with multiple gaps and challenges yet to be addressed, and here synthesised in Box 1 and Box 2. These identified gaps and challenges are described more in detail in the subsequent subsections.

Box 1. Main identified gaps

- Uncertainty of the performance of some AF products and their environmental effects.
- Uncertainty on the required biocidal load, generally too high.
- Uncertainty on their effects in non-target species.
- Uncertainty on the influence of location and associated environmental factors and the operational profile of the boat.
- Lack of approved AF technologies, rather than just substances listed in Annex 1 of AFS Convention.
- Lack of roadmap to suitable AF strategy selection, particularly for recreational boats.
- Lack of services and facilities for enhanced management of biofouling.
- Feasibility of some products and services for the sector of recreational boats.
- Scarce knowledge on the topic in certain sectors or stakeholders.

Box 2. Main challenges

- Applicability of certification and inspection regimes for recreational boats.
- Alignment between industries, authorities, scientific community, and final users.
- Regulation and enforcement in regions, such as the Mediterranean, with multiple nations and overcoming geopolitical issues that may arise.
- Implementation and enforcement in certain sectors, e.g., recreational boating.
- Engagement and behavioural changes, increasing perceived risk by end users.

Limitations and uncertainties of antifouling coatings

It has been demonstrated that antifouling paints, in particular the ones containing biocides, can be toxic for non-target organisms, including planktonic crustaceans like the brine shrimp or harpacticoid copepods, macro- and microalgae, and fish [2, 58, 59, 86, 138], causing major physiological impairments even at the lowest tested concentrations (Santos-Simón et al., submitted.). Furthermore, some fouling species demonstrated higher tolerance to biocide-based coatings [23, 91, 92, 104]. This tolerance phenomenon has major biosecurity implications, since some of the studied species are considered NIS. Besides, in-field performance testing experiments suggested that the selected biocide-based coating did only reduce the coverage of biofouling in the short term, but hosting higher NIS ratios during the high boating season, and failed to meet performance goals in the long term [23, 104]. In fact, these studies together with that from [40] remark that common AF measures, e.g., application of copper containing coatings, are often highly selective and, even if effective at controlling the growth of certain species, they fail to prevent the growth and transport of others.

In fact, determining the effective concentration for the prevention of all fouling organisms can be challenging. Biocidal coatings leach compounds to the environment, ideally at a defined and constant rate which ensures the effective concentration of active compounds at the surface. Estimates have been done on the release rate from antifouling coatings [109, 114] and further experiments on their chemical behaviour of showed that environmental factors, such as salinity and temperature, affected the release of metals from the coatings to the water [61, 111, 112, 137], potentially affecting the toxicity [32, 108], durability, and performance of the tested coatings. Therefore, these factors are of particular importance for suitable AF selection based on geographical location and risk mitigation under a climate-change scenario. Furthermore, coating preparation and application could also alter the release of metals to the environment and, therefore, it should be considered as an important variable for efficient and safe antifouling use.

Regulations on biofouling and antifouling systems

Having reviewed the main regulatory instruments, it is evident that the main gap regarding biofouling is the lack of a global international binding framework that ensures the application of measures and approved antifouling treatments to control or, at least, minimise the introduction of non-indigenous species.

Biofouling Convention is expected to be some day the sibling Convention of the BWM Convention. As described before, the ongoing steps on biofouling regulation resemble the origins of BWM Convention. In both cases, first regulatory attempts started with non-binding instruments that provided guidance to both flag and coastal States. Like the BWM Convention, current guidelines for biofouling consider vessel design as a key factor; management plan and record book as the main tools; and describe different AF measures, whilst referring to various considerations on the selection, installation or application, and their maintenance. It refers to the AFS Convention as supportive, despite it only lists two banned substances; conversely, a list of approved technologies similar to that from BWM Convention and New Zealand's CRMS for vessels [77] is missing, even if some pilot programmes have proved it feasible [93]. Indeed, a list of approved systems could be more suitable to face all the new technological developments in the field of antifouling coatings, which include alternative biomimetic surfaces, enzymatic inhibitors, and non-biocidal coatings, such as foul-release and superhydrophobic coatings [110, 135, 136] Furthermore, IMO guidelines describe factors to be taken into account for the selection of AF coatings, but do not provide a roadmap to the final choice, as done for example by the National Institute for Public Health and the Environment of the Ministry of Health, Welfare and Sport of the Dutch Government [135]. In fact, the current plethora of available market products and solutions only contributes to blurry the choices of boat owners. Recently, under the scope of the GEF-UNDP-IMO GloFouling Partnerships Project, the lack of clarity on available solutions has been recognised as a major gap, and in that same document, clear efforts have been done to tackle it [42].

Cultural measures for effective regulation enforcement

Ensuring commitment from the involved stakeholders implies adopting further measures other than just enforcement. Cultural tactics generally are understood as practises that prevent or delay pest outbreaks, including site selection, scheduling and planning management tactics, and increasing efficacy by removing sources of the pest [22, 23], yet they can include other measures, such as access to information, outreach programmes, improvement of services and maintenance facilities, training courses and technical assistance, etc. Some of these measures have accompanied the implementation of international measures and examples of it are the BWM Convention, which explicitly established the obligation for technical assistance (Art. 13(1); [54]), or the implementation of the CRMS by the MPI, with targeted outreach campaigns [107]. It requires specific resources to be allocated for the purpose assigned to (a) infrastructure improvement, (b) outreach or engagement programmes, and (c) technical assistance and information points.

Aligning drivers of interest

Motivations behind the need of biofouling control and its regulation vary according to the interested parties and it can be challenging to set common minimum standards satisfying their demands. The review by [30] concluded that, despite unified wills to regulate and manage biofouling do actually exist, the resolution of the gathered information and the areas of utmost concern compose the main discrepancies across parties. Cost saving, safety at sea, biosecurity, biodiversity, and conservation are not always shared priorities and fall within interests of particular sectors. Whilst industry seeks optimization of operational performance and cost savings, for authorities and environmental managers, biosecurity risk reduction is the main driver. However, overcoming this discrepancy appears reasonable and feasible. Greater uncertainties surround the sector of recreational boating, as there has been less emphasis on understanding them, as well as less awareness on the matter. As other stakeholders incorporate to the equation, different drivers may emerge. It should also be remembered that biofouling is a natural process and these organisms are an important part of the marine ecology. There are opportunities to design and manage in-water structures, in such a way that biofouling may contribute to it [66, 99].

Finding the balance

Balancing risks has never been an easy task and establishing acceptable environmental risks is no exception. Defining a middle ground in biofouling management implies counterpoising biosecurity risks to those from antifouling systems' implementation, both under the umbrella of environmental protection [42]. Additionally, measures need to be feasible and practical, whilst meeting the established minimum environmental standards. Due to concerns on the effects of certain biocides, antifouling technologies are shifting towards alternative novel solutions and, as seen above, certain regional governments are promoting projects in doing so [93]. However, currently existing biofouling management strategies are not protective of biosecurity goals (Davidson et al., 2016) and, although some exceptions exist [25, 77], the scale is unbalanced.

Geopolitics

Effective environmental protection and regulation requires targets to be reconciled with social, economic, cultural, and political needs [60]. In practise, where regions have inherent geopolitical complexity and a wide range of priorities, like the case of the Mediterranean Sea, challenges arise, hampering the development of a common shared legal framework. The Mediterranean is an interesting case study from the jurisdictional perspective as, once declared, the EEZs of the over 20 countries leave no space for High Seas. Coastal States have "sovereign rights for the purpose of exploring and exploiting, conserving and managing the natural resources, whether living or non-living, of the waters superadjacent to the seabed and of the seabed and its subsoil, and with regard to other activities for the economic exploration and exploitation of the zone" (UNCLOS, Art. 56 [129]). Furthermore, coastal States have legislative and enforcement jurisdiction with regard to the protection and preservation of the marine environment, including matters defined by international law (UNCLOS, Art. 56(1)b [129]). This is a double-edged sword: even if it offers an unprecedented opportunity for environmental jurisdictional matters [60], disputes over EEZ's boundaries entail legal uncertainty over the complex jurisdictional scenario of the region and the applicable rules and standards aiming for effective environmental protection [3].

The interaction between the described challenges is illustrated in Fig. 2.

Learnings and proposals

Proposals to some of the existing gaps

A tiered compliance framework is recommended to address the complexity of the issue and the multiplicity of parties involved. The subsequent proposals, therefore, are aimed at different levels and with differentiated obligations for specific targets. First, gaps related to antifouling systems could be addressed by creating a list of approved antifouling products and technologies by designated bodies [e.g., under development Approved Biosecurity Treatments" (MPI-STD-ABTRT); BWM approved systems], which could positively contribute to a shift in the market and greater regulation enforcement regarding the products, taking as a reference the procedures of ballast water treatments. Environmental safety certifications and periodical revisions on the available solutions, particularly those containing biocides, could contribute to ease the choice of more environmentally friendly alternatives whilst redirecting the global antifouling market towards sustainability and fuel associated technological innovation. Additionally, requirements to include suitability of use of a product, i.e., information on environmental conditions and geographical location, boat area, etc., could help to enhance the performance of the product, contribute to environmental protection, and facilitate the choice of appropriate solutions. These measures could contribute to reducing the total biocidal load of some products or adequate it to certain environments, including additional limits to copper usage. Besides, it is required to

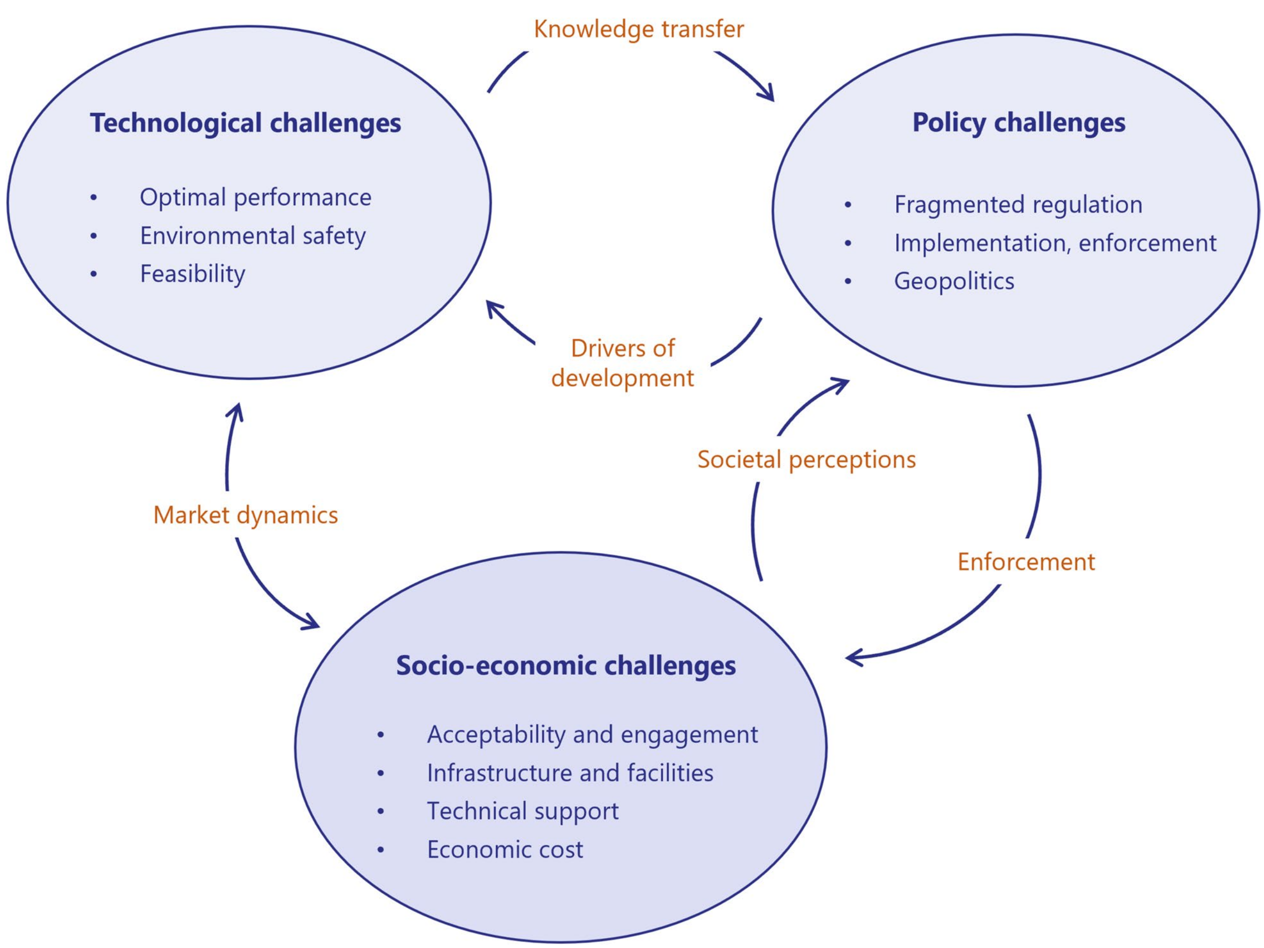

Fig. 2 Main challenges to be faced for effective biofouling management, Arrows represent interactions amongst compartments

consider the effects of other compounds in paint formulations, which, despite not being considered active compounds, could contribute to the overall toxicity of the products (mainly low-molecular-weight aromatic compounds, such as naphtha, ethylbenzene, and xylene). Ecotoxicological tools are key to support such decisions and, therefore, a key instrument to address antifouling related uncertainties. Furthermore, certified sellers, appliers, and managers could improve product selection and their suitable application, as well as waste reduction and management, extending durability of the selected systems and minimising environmental risks.

Second, an additional supportive measure for suitable AF selection would be the development of a roadmap to guide users in the decision-making process. Generally, the information available tends to summarise the types of AF systems [11, 42, 116, 121] and the most recent contribution to a guided decision could be that from Wezenbeek et al. [135], whose decision-tree has been updated here in Fig. 2, to cover the latest findings, including those from Culver et al. [22], GEF-UNDP-IMO GloFouling Partnerships Project [42], Lagerström et al. [63], and Santos-Simón (submitted.), amongst others. Figure 3 has been conceived as a proposal to assist in the decision of coating selection, considering multiple factors, such as the vessel operational profile, maintenance, boat area, and environmental conditions (e.g., salinity, water temperature). Ensuring access to this type of information by final users is key to optimise AF measure selection.

Third, creating a network of information and promoting dissemination activities would, ultimately, help to increase awareness and promote commitment amongst boat owners. In fact, tools, such as the guidelines by the IMO [42] with clear language and illustrative information, are essential to translate policy and scientific outcomes to final users. Still, enhanced engagement from the stakeholders is necessary, which could be achieved by allocating funds to infrastructure improvement and design of outreach campaigns with different goals. Indeed, GEF-UNDP-IMO GloFouling Partnerships Project, aside of acting as an authoritative knowledge hub, also serves as a model for stakeholder engagement. Accessible cleaning and waste management facilities in ports and marinas areas must reduce pollution and biosecurity risks, backed up by management and risk reduction plans. Besides, having technical staff in charge of applying those plans and of assisting final users in their maintenance activities, accompanied by training courses could contribute further to reach this goal. Finally, clear procedures for vessel inspections and surveys are required where regulations are in force, similar to those proposed by Georgiades & Kluza [44], although further steps could be done by marina and port managers as implied responsible authorities. This later step also requires investing in a network of

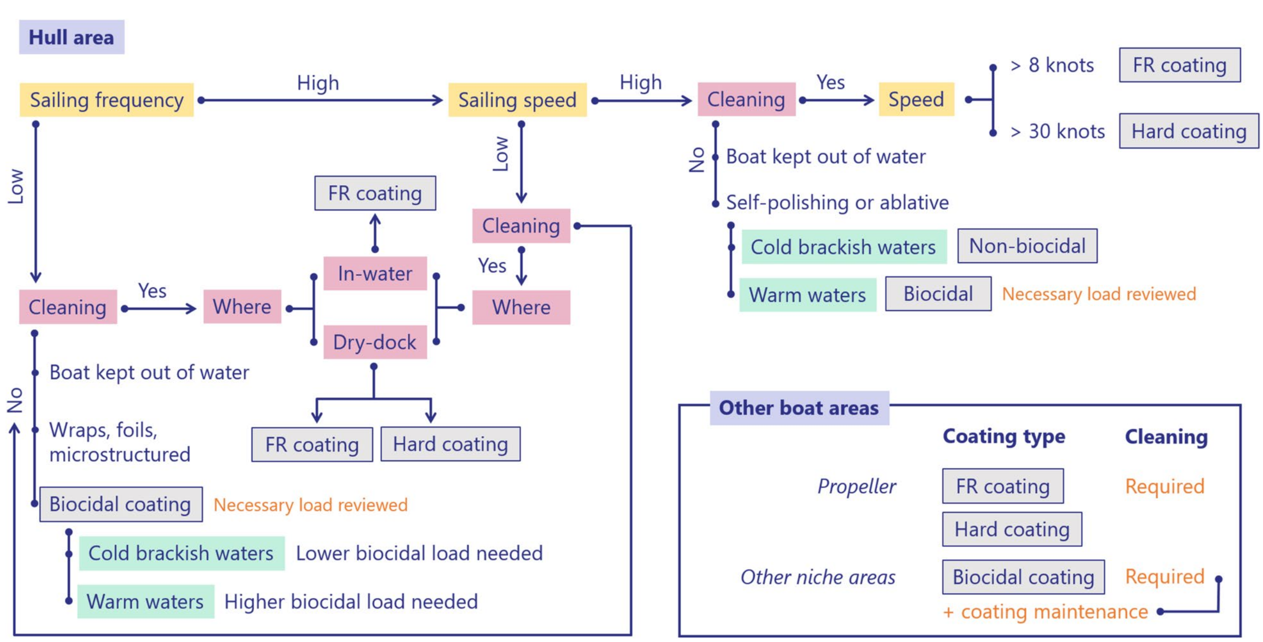

Fig. 3 Decision tree for suitable antifouling coating selection for recreational boat owners. Modified from [135], including recent updates from reviewed works [42], Washington State Department of Ecology,). Colour indicates the class of factor on the decision process: yellow for operational profile; pink for maintenance (cleaning); green for environmental factors and powder blue for boat area. The final coating choice is indicated in grey background

certified personnel and important efforts need to be done regarding engagement and outreach. Widely available, standardised information provided by the IMO, through the GEF-UNDP-IMO GloFouling Partnerships Project knowledge hub, addressing stakeholders, society and decision-makers at global level, contribute to overcome major challenges, in particular larger geopolitical issues (see also Fig. 2).

Main conclusions

The current uncertainties and challenges in biofouling management leave a gap that entails legal uncertainty over effective environmental protection, therefore highlighting the urgent need of regulatory instruments on the matter. Biofouling regulations are a necessary legal instrument and achieving it should be regarded as a priority. Recent events are leading the way and the development of a legally binding instrument on biofouling has been approved in the MEPC 83º, held on April, 2025.

These regulations, however, should naturally rely on different type of actions, as listed above, which requires an important reshaping of it was conceived until now, and includes (1) clear and accessible information and provision of reliable tools, (2) engagement activities, (3) infrastructure improvement, (4) solid network of certified personnel and product sellers, and (5) implementation of management plans.

Abbreviations

AF	Antifouling
AFS Convention	International convention on the control of harmful antifouling systems on ships
BDP	Biocidal products directive
BFMP	Biofouling management plan
BFRB	Biofouling record book
BWM Convention	Ballast water management convention
CBD	Convention on biological diversity
CRMS	Craft risk management standard
CSLC	California State lands commission
DAFF	Department of Agriculture, Fisheries and Forestry
ECHA	European chemicals agency
EEZ	Exclusive economic zone
HELCOM	Helsinki commission
IMO	International maritime organisation
MARPOL	International convention on the prevention of pollution from ships
MARS	Maritime and aircraft reporting system
MEPC	Marine environmental protection committee
MoU	Memorandum of understanding
MPI	Ministry of primary industries
MSFD	Marine strategy framework directive
NIS	Nonindigenous species
OILPOL	International convention on pollution of sea by oil
REACH	Registration, evaluation, authorisation and restriction of chemicals
TBT	Tributyltin (TBT)
UN	United Nations
UNCLOS	United Nations convention on the law of the sea
UNEP	United Nations environment programme
US EPA	United States environmental protection agency
WFD	Water framework directive

Acknowledgements
The authors would like to thank Imanol Basterrechea Iribar for getting the teams in contact and, thus, fuelling such collaboration; and Emilio Mancuso for providing high-quality underwater pictures that have been used for illustrative and dissemination purposes. The authors would like to thank the anonymous reviewers and their assessment significantly contributed to improve this work.

Author contributions
MSS, MOZ, AM, and AFG conceived the ideas and conceptualised the research; MSS lead the investigation, with the support and participation of the other authors. The structure was designed by MSS, MOZ, AM, and AFG, and culminated with the review of works of interest. MSS performed the formal analysis and visualisation, which were ultimately validated by MOZ, AM, and AFG. The writing of the original draft was done by MSS and the review and editing by the remaining authors, MOZ, AM, and AFG. Funding acquisition was done by MOZ and SS.

Funding
This study was funded by the Basque Government through a predoctoral grant to MSS (PRE_2020_1_0373), and through the grant to CBET+consolidated research group (IT1743-22). It was additionally supported as part of the research project TED2021-132109B-C21 funded by MCIN/AEI/https://doi.org/10.13039/501100011033 and EU NextGenerationEU/PRTR; and through Knowledge Generation Projects 2023 (PID2023-149939NB-C33), funded by the Ministry of Science, Innovation and Universities (MCIU), State Agency for Research (AEI) and European Regional Development Fund (ERDF). Finally, this work was supported by the European Union's Horizon Europe HORIZON-CL6-2024-BIODIV-01 project 'GuardIAS—Guarding European Waters from IAS', under Grant Agreement No. 101181413.

Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

Received: 18 March 2025 Accepted: 6 July 2025
Published online: 26 July 2025

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