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Citation for the original published paper (version of record):
Hou, P., Ytreberg, E., Lagerström, M. (2026). Chemical mapping and hazard assessment of marine hull coatings on the EU market. Marine Pollution Bulletin, 230.
http://dx.doi.org/10.1016/j.marpolbul.2026.119799

Marine Pollution Bulletin 230 (2026) 119799

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Chemical mapping and hazard assessment of marine hull coatings on the EU market

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ARTICLE INFO

Keywords:
Antifouling paints
Marine hull topcoats
Biocides
Biocidal products regulation
Environmental hazard assessment

ABSTRACT

Marine hull coatings are applied onto ship and yacht hulls to protect them from biofouling and abrasion. As these degrade with time, they may cause adverse effects on the marine environment. In this study, hull topcoats from six major manufacturers on the EU market were categorized and assessed for inherent hazard using a practical product-level assessment approach based on chemical information disclosed in safety data sheets. Biocide-containing coatings were found to dominate both segments, representing 83% of ship coatings and 88% of yacht coatings, and were significantly more hazardous than biocide-free alternatives. The calculated hazard varied substantially between biocidal products and found to depend on the type and number of biocides included in the formulation. While biocides accounted for the majority of the environmental hazard of biocidal products, 95% in ship products and 70% in yacht products, additional hazardous substances were identified in both biocidal and biocide-free products, along with their functional roles and substitution potential. These findings offer valuable insights for future regulatory and industrial practices aimed at improving the sustainability in marine coatings.

1. Introduction

Marine coating systems are essential for protecting vessel hulls and ensure optimal performance in marine environments (Chambers et al., 2006). Marine coatings are often applied in multiple layers on the hull, each with a specific role (Lambourne and Strivens, 1999), and topcoats are the outermost layers on the hull. These coatings are typically functionalized to provide either antifouling (AF) or abrasion-resistant properties (Chambers et al., 2006). AF coatings prevent the attachment of marine fouling organisms known as biofouling, thus avoiding increased frictional drag and fuel consumption (Schultz, 2007). In contrast, abrasion-resistant coatings prioritize mechanical durability to withstand physical impacts and harsh operating conditions e.g. in ice conditions (Watermann et al., 2021).

As the topcoat is the outermost layer exposed to seawater, it can intentionally or unintentionally leach substances into the marine environment (Carrier et al., 2023). The extent of leaching depends on the chemical composition of the coating, i.e. which substances it contains and how these are bonded within the matrix, as well as the overall durability of the paint film as this will govern the degradation rate of the coating. Both AF and abrasion-resistant coatings typically contain solvents, pigments and binders (Fig. 1). While solvents evaporate during application, binders and pigments remain in the dry film, influencing both performance and environmental impact.

Pigments are organic or inorganic solids incorporated into topcoats to provide specific functions (Abel, 1999). For AF coatings, biofouling prevention is typically achieved through the use of biocidal pigments. The resulting intentional release of biocides into the marine environment upon immersion deters the settlement of fouling organisms through toxic means but is also the cause for environmental concern (de Campos et al., 2022). The usage and release of biocides to the marine environment has been shown to be substantial and studies have reported that commonly used biocides can adversely impact non-target organisms (de Campos et al., 2022; Amara et al., 2018; Martins et al., 2018; Viana et al., 2020). Within the EU, 14 biocides (product type 21), also termed active substances, are registered under the Biocidal Products Regulation (BPR) (Regulation (EU) No 528/2012), with 10 currently approved. All approved biocides are subject to re-approval every 10 years, and such a process is currently ongoing. These biocides are added to the paint to control hard fouling organisms (e.g., barnacles, tubeworms, mussels) and soft fouling organisms (e.g., bacteria and algae). Most antifouling coating currently available on the market typically incorporate a main

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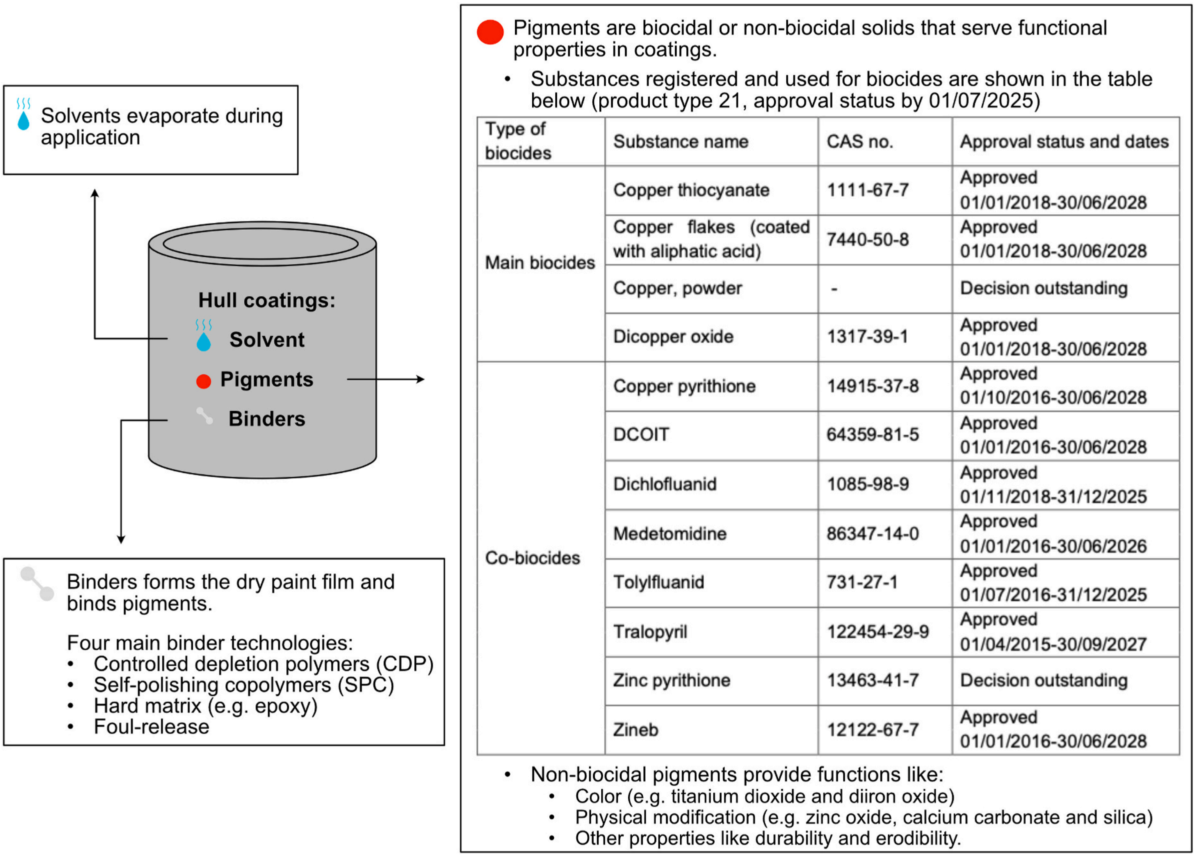
https://doi.org/10.1016/j.marpolbul.2026.119799
Received 28 January 2026; Received in revised form 15 April 2026; Accepted 22 April 2026

(or primary) copper-based inorganic biocide in combination with one or more organic or organometallic co-biocides. The main biocide provides broad-spectrum AF protection, with dicopper oxide (Cu_2O) dominating the market (Brooks and Waldock, 2009; Paz-Villarraga et al., 2022). Co-biocides are added to broaden the AF spectrum, particularly targeting algal species which are copper-resistant (Voulvoulis, 2006). Tralopyril (approved in 2015) and medetomidine (approved in 2016) are organic biocides included on the EU list of approved active substances, tralopyril offers broad-spectrum activities, whereas medetomidine is used to specifically deter barnacle settlement (Dahlström et al., 2000; Oliveira et al., 2014). Non-biocidal pigments are added for properties such as providing color, durability (e.g. UV resistance), physical modifications (e.g. extenders or fillers) and controlled erodibility (Fig. 1). Zinc oxide (ZnO) is frequently added in AF coatings as an extender to adjust hardness and density of the film, and while it is not classified as a biocide under the BPR, it exhibits toxic properties (Karlsson et al., 2010). Zinc (Zn) has been adopted as a priority substance by the Baltic Marine Environment Protection Commission (Helsinki Commission, (HELCOM), due to concerns about its environmental impact (HELCOM, 2025; Ytreberg et al., 2010).

Binders hold pigment particles together, form the continuous film upon drying, and govern biocide release mechanism (Zhou, 2015). Four main binder technologies exist: controlled depletion polymers (CDP), self-polishing copolymers (SPC), hard epoxy-based matrixes and foul-release coatings (FRCs). CDP and SPC coatings are designed to erode during service, ensuring a continuous release of biocides and thereby providing effective protection against biofouling (Weber and Esmaeili, 2023). In contrast, hard epoxy-based coatings are insoluble and provide high durability and abrasion-resistance (Weber and Esmaeili, 2023). When incorporated with biocides, they allow water to penetrate and dissolve biocides, then release them by diffusion (Zhou, 2015). Concerns over biocide toxicity have driven innovation toward biocide-free foul-release coatings (FRCs), which rely on silicone polymers to create low-energy surfaces that deter organism attachment (Lejars et al., 2012). Currently, polydimethylsiloxane (PDMS) technology dominates the FRC market, while fluoropolymer-based systems remain rare and are limited to only a few products (Lagerström et al., 2022). Though initially developed without biocides due to technical limitations (Ciriminna et al., 2015), biocidal FRCs have been commercially available since 2013 (Lagerström et al., 2022). All binder types, regardless of the addition of biocides, can pose environmental concerns as they degrade. Erosion, weathering and maintenance of the coatings can contribute to microplastic emission because of their polymeric nature (Muller-Karanassos et al., 2021). Silicone-based FRCs may contain and release unbound silicone oils and *per*- and polyfluoroalkyl substances (PFAS) (Lagerström et al., 2022; Nurioglu et al., 2015; Piazza et al., 2018), while bisphenols in epoxy resins may leach from hard matrix coating formulations (Wezenbeek et al., 2018).

Even though the BPR requires comprehensive risk assessments and authorization procedures before any biocidal product may be placed on the market, the current reporting and evaluation processes only focus on the emission of biocides and zinc (Lagerström et al., 2020). Biocide-free coatings, on the other hand, do not require prior approval for marketing and emissions of substances which do not fall under the legal classification of biocides do not have to be disclosed. Ecotoxicological studies, involving coating leaching into seawater and subsequent exposure of marine organisms to the leachate, can provide valuable information on the potential hazard of different coatings by assessing adverse effects on non-target organisms and serve as a comparison tool for evaluating relative toxicity between products (Ytreberg et al., 2010; Piazza et al., 2018; Karlsson et al., 2010). However, these methods are time-consuming and costly, requiring expertise in ecotoxicological assays, which means only a limited number of products have been assessed (Ytreberg et al., 2010; Karlsson et al., 2010).



Solvents evaporate during application

Binders forms the dry paint film and binds pigments.

Four main binder technologies:
- Controlled depletion polymers (CDP)
- Self-polishing copolymers (SPC)
- Hard matrix (e.g. epoxy)
- Foul-release

● Pigments are biocidal or non-biocidal solids that serve functional properties in coatings.

- Substances registered and used for biocides are shown in the table below (product type 21, approval status by 01/07/2025)

Type of biocides	Substance name	CAS no.	Approval status and dates
Main biocides	Copper thiocyanate	1111-67-7	Approved 01/01/2018-30/06/2028
	Copper flakes (coated with aliphatic acid)	7440-50-8	Approved 01/01/2018-30/06/2028
	Copper, powder	-	Decision outstanding
	Dicopper oxide	1317-39-1	Approved 01/01/2018-30/06/2028
Co-biocides	Copper pyrithione	14915-37-8	Approved 01/10/2016-30/06/2028
	DCOIT	64359-81-5	Approved 01/01/2016-30/06/2028
	Dichlofluanid	1085-98-9	Approved 01/11/2018-31/12/2025
	Medetomidine	86347-14-0	Approved 01/01/2016-30/06/2026
	Tolylfluanid	731-27-1	Approved 01/07/2016-31/12/2025
	Tralopyril	122454-29-9	Approved 01/04/2015-30/09/2027
	Zinc pyrithione	13463-41-7	Decision outstanding
	Zineb	12122-67-7	Approved 01/01/2016-30/06/2028

- Non-biocidal pigments provide functions like:
  - Color (e.g. titanium dioxide and diiron oxide)
  - Physical modification (e.g. zinc oxide, calcium carbonate and silica)
  - Other properties like durability and erodibility.

Fig. 1. Composition of hull topcoat products (Lambourne and Strivens, 1999; Abel, 1999).

To address this gap and enable hazard screening of most products on the EU market, this study introduces a simplified approach for evaluating chemical risks beyond biocides and zinc for any coating. The method uses openly available information provided in its Safety Data Sheets (SDSs) and compare potential hazard through an indicative hazard score, termed the Product Hazard Potential (PHP), which can serve for comparison and prioritization of products. In this study the types and frequency of different topcoats available for ships and yachts from main paint manufacturers within the EU were investigated. Identified topcoats were subsequently categorized based on the presence (or not) of biocides and their binder technology and their PHP-values were compared to identify the less hazardous coating type. For each topcoat category, the main substances driving the calculated PHP, their function in the formulation and the possibility for their substitution were also investigated.

2. Methodology

2.1. Product data collection and coating categorization

Safety data sheets (SDSs) for all ship and yacht topcoats intended for application as the outermost layer of the underwater part of the hull surface were collected from the websites of six major paint companies on the EU market. These companies were identified based on the variety of their topcoat portfolios (> 5 products) marketed in the EU, using product listings from both Lloyd's Register, an international maritime classification and compliance organization that certifies marine coatings, and the biocidal products catalogue of the French Agency for food, Environmental and Occupational Health & Safety (Lloyd's Register, 2026; Anses, 2025). Only products marketed for use in the EU and accompanied by accessible SDSs were included. SDS information was collected between 2024/05/14–2024/07/20. The number of products was determined based on unique product codes. If a product had different versions of SDSs for the same product name but with different product codes, the latest version was chosen.

Products were categorized by market segment (ship or yacht) based on their intended use (Table 1). As yachts with a hull length $\geq$ 24 m (79 ft) are classified as 'superyachts', they are categorized as commercial vessels for regulatory purposes (Wezenbeek et al., 2018). Products for superyachts were therefore included in the ship segment.

To further describe the types of available products, the identified topcoats for the ship and yacht segments were firstly categorized based on the presence or absence of biocides (Fig. 2). Secondly, they were grouped based on their binder technologies. CDP, SPC and hard epoxy-based matrixes were grouped together and termed as traditional binder coatings (TBC), whereas FRC were treated as a separate category due to their distinct properties and mode of action. In total, this study thus identifies four main coating types: biocidal TBC, biocidal FRC, biocide-free TBC and biocide-free FRC. For the biocidal TBCs, products were further classified according to the main biocide used. Coatings containing Cu_2O and CuSCN were categorized as inorganic copper-based, whereas products lacking a primary inorganic copper-based biocide (e.g. those using tralopyril or combinations of organic biocides) were considered alternative biocide(s)-based. Moreover, Traditional inorganic copper-based coatings were divided into subcategories according to the number of incorporated co-biocides.

Table 1
Number of products on the European market identified from the investigated coating companies and by market segment (yacht or ship).

Company	Ship segment	Yacht segment	Total
Hempel	41	36	77
International	17	29	46
Chugoku	16	13	29
Jotun	14	16	30
PPG	11	0	11
Boero	5	14	19
Total	104	108	212

For comparison with the global market, a compilation of all products certified by Lloyd's Register were collected on 2025-09-16. The Lloyd's dataset covers both ship and yacht products from 16 countries and includes information on the identity of included active substances. The dataset was filtered to remove duplicates, ensuring a count of unique products (Supplementary material File S1). The frequency of occurrence of each identified biocide was also derived.

2.2. Chemical information processing

The processing of the chemical information is summarized in step 1 of the flowchart of Fig. 3. First, information on hazardous chemicals from each product's SDS was extracted to estimate its environmental hazard. SDSs are legally required for all substances or mixtures classified as hazardous, those identified as Persistent, Bioaccumulative and Toxic (PBT) or very Persistent and very Bioaccumulative (vPvB), and for substances on the candidate list for authorization (ECHA, 2020). Python was used to extract chemical information from all SDSs resulting in the identification of 168 unique chemicals. These were then classified into four categories based on their function in the formulation as either binders ($n = 71$), solvents/thinners/diluents ($n = 40$), biocides ($n = 10$) or additives ($n = 47$). The binder category also included copolymers, curing agents and curing catalysts, which are either components of or incorporated within binders. Copper oxide (CuO), the oxidative product of Cu_2O, was found in some coating formulations in small amounts (typically $\leq$5 Wt%) as an impurity in technical-grade Cu_2O. Although not registered as a biocide in the EU, it was classified as such in this study due to the antifouling properties of the copper ions. Chemicals that were classified as additives included color, fillers, antioxidants, plasticizers, rheology additives, etc.

When a product (with the same product code) was available in multiple color options, and each color had its own SDS, the red-colored version was selected to avoid duplication. However, if red was not available, the black-colored version was used instead. If only one SDS was provided for all colors of the same product, this single version was used for calculation. The selection of color only applied when multiple color options shared the same product code, products with distinct codes were considered unique products. White-colored products were treated as unique products because they typically have different biocidal composition. It is mandatory to report substances with concentrations $\geq$0.1 *w*/w % that are classified with severe hazards under the EU's classification, labelling and packaging (CLP) of substances and mixtures (Regulation (EC) No 1272/2008). However, manufacturers are also encouraged to report substances present at lower concentrations on a voluntary basis. The reporting procedure of chemicals in SDSs therefore varied among manufactures. To enable a fair comparison of products regardless of manufacturer, only chemicals with concentrations $\geq$0.1 *w*/w % were retained for further calculation in this study.

2.3. Product Hazard Potential

2.3.1. Product Hazard Potential calculation

A hazard potential calculation approach was adopted from the concentration addition (CA) concept to enable the comparison of hazard posed to the marine environment by the dry paint film of different topcoat products. The CA concept has been widely accepted for predicting the toxicity of mixtures, it is also applied by the CLP Regulation for the hazard classification of mixtures (Regulation (EC) No 1272/2008). This method assumed that the contribution of each component to the overall mixture toxicity is proportional to its fraction (C_i) in the mixture and its individual toxicity, expressed as the effect concentration (EC_i) (Backhaus and Faust, 2012):

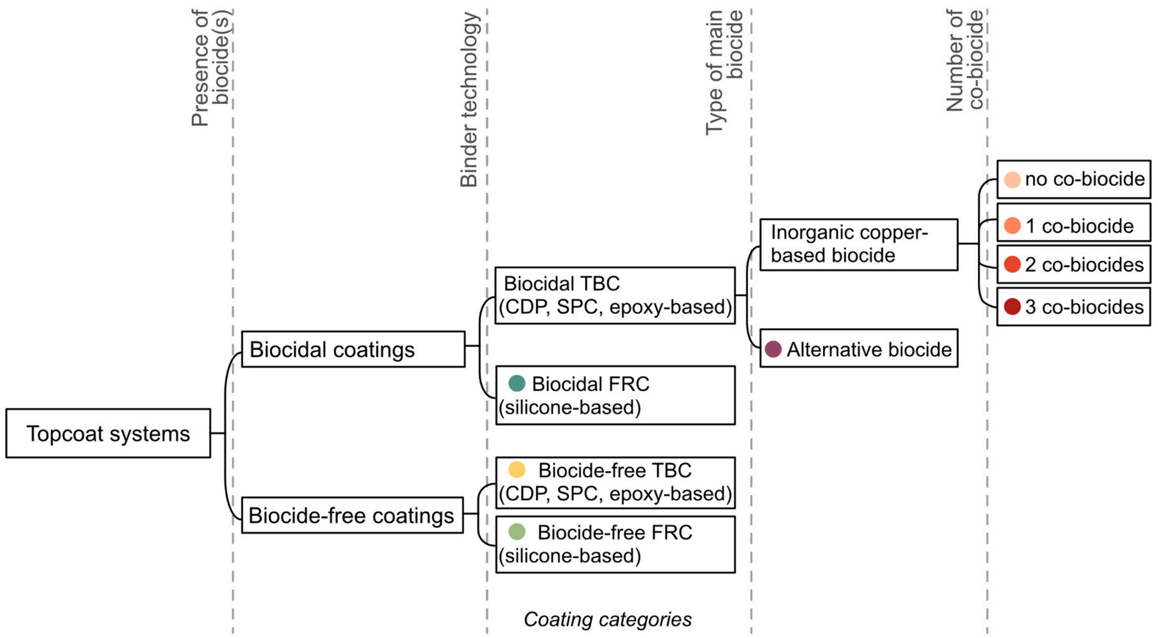


Fig. 2. Coating categorization. (TBC: traditional biocidal coating; FRC: foul release coating; CDP: controlled depletion polymer; SPC: self-polishing polymer).

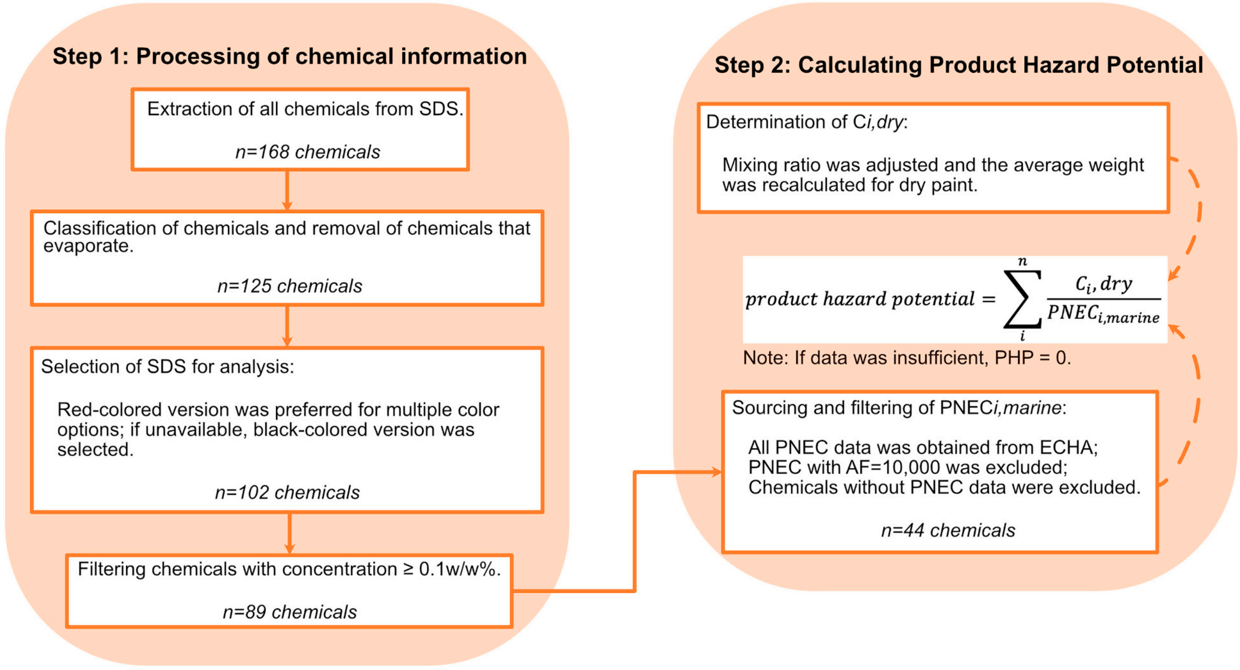


Fig. 3. Overview of the methodology for extracting chemical data from Safety Data Sheets (SDS) and calculating Product Hazard Potential (PHP) values using effect-based threshold values (Predicted No-Effect Concentrations, PNECs) and measured dry concentrations (Ci) of chemicals.

$$mixture\ toxicity = \sum\nolimits_i^n \frac{C_i}{EC_i} \tag{1}$$

To estimate the hazard potential of dry coating films to marine organisms, here termed the Product Hazard Potential or PHP, an equation was adapted from Eq. (1), whereby EC was replaced with the PNEC for marine seawater (Eq. (2)).

$$Product\ Hazard\ Potential = \sum\nolimits_i^n \frac{C_{i,dry}}{PNEC_{i,marine}} \tag{2}$$

Chemicals, for example solvents, that would not be present in the dry paint were excluded from the calculation and the average weight percentage of the remaining chemicals ($C_{i,dry}$) were recalculated before incorporation into the equation. The previously described classification of chemicals based on function enabled the identification of solvents and volatile chemicals expected to evaporate during application. For products consisting of multiple components, the required mixing ratios prior to application were incorporated into the calculations to adjust the percentage of chemicals after mixing. One biocidal product from the yacht segment was removed from calculation as the mixing ratio of its components was not specified. Biocide concentrations were obtained either from SDSs or from registrations with governmental agencies (Anses, 2025). Registrations provided exact concentrations, while SDSs often reported ranges; in such cases, average concentrations were calculated and used.

PNEC$_{i,marine}$ is the predicted no effect concentration of ingredient *i* in the marine environment, below which no adverse effects of concern are expected to occur (ECHA, 2025b). The PNECs for biocides were retrieved from the emission scenario documents accepted by ECHA for the environmental risk assessment of antifouling products. For all other chemicals, available PNECs were retrieved from the European Chemicals Agency (ECHA) database (ECHA, 2025c,d), and only those with an assessment factor (AF) below 10,000 were included directly to reduce the uncertainty in the calculated PHP. An AF of 10,000 indicates limited toxicity data and a high level of uncertainty (European Commission, 2017). Chemicals with no available PNECs were not included in the calculation. If collected data was not sufficient to derive the PHP of a product, for example all components were solvents, the PHP of the product was assigned a value of "0" by default. It is worth noting that a PHP value of 0 does not imply an absence of hazard, but rather that no hazard could be identified based on the available information due to insufficient data.

To provide a benchmark for current biocidal products, the PHP of three organotin-based coatings and three irgarol-containing coatings were calculated as reference points (Supplementary material File S1). Organotin compounds function as broad-spectrum biocides, whereas irgarol serves as a booster biocide (Thomas, 2009). Both organotin compounds and irgarol were prohibited by the International Maritime Organization due to their adverse effects on the marine environment (IMO, 2001). The PNEC value for the organotin biocide was sourced from the EU's Environmental Quality Standards (EQS) technical documentation (European Commission, 2005), and the PNEC for irgarol was obtained from the ECHA website (ECHA, 2025c).

2.3.2. Product Hazard Potential evaluation and contributing chemicals

To compare the hazard of the different products depending on their intended market and coating type (Fig. 2), stepwise comparisons were performed. Firstly, differences between ship and yacht products were analyzed. The PHP for biocidal and biocide-free coatings were compared separately using a Mann-Whitney *U* test, and the difference in the concentrations of inorganic copper-based biocides, expressed as the concentrations of copper ion, were compared between segments (Mann-Whitney U test). Secondly, differences in PHP between biocidal and biocide-free products within each segment were investigated using the same test. Non-parametric tests were chosen as the data was non-normal and the sample size of each categories varied substantially. Subsequently, differences among the coating categories within each segment were assessed with the Kruskal-Wallis test, followed by Dunn's post hoc test. Finally, to investigate the influence of biocide composition, the PHP of biocidal TBCs with different biocidal profiles were compared. The concentrations of inorganic copper-based biocides, expressed as concentrations of copper ion, were compared (Mann-Whitney *U* test) to determine whether the addition of co-biocides results in a significant change in copper concentration. Linear regression analysis was also performed to investigate if a correlation between the number of biocides and the PHP of traditional inorganic copper-based coatings could be distinguished. A *p*-value of less than 0.05 was considered statistically significant for all the above tests. Statistical analyses were performed using SPSS (Version 29.0 2.0).

The contribution (in percent) of each individual chemical to the PHP of a given product ($\frac{C_i}{PNEC_i}/PHP$) was derived. For biocidal products, this analysis was also performed excluding biocides as they were found to strongly influence the PHP, thereby masking the contribution of other substances. Chemicals that contributed $\geq$10% of the PHP in any product when biocides were not considered were compiled and their regulatory status and potential replacement investigated.

3. Results and discussion

3.1. Coating type and biocide profile

The vast majority of products for the ship segment (86 out of 104, or 83%) were biocidal. Similarly, for the yacht segment, 95 out of 108 (88%) products fall into this category (Fig. 4). Data from the Lloyd's Register reflects this same trend, with 426 out of 457 products (93%) being biocidal, suggesting the global industry heavily relies on biocides. Particularly, biocidal TBC, i.e. coatings with traditional binder systems, far outnumber the other coating types for both the ship (79 products) and yacht (95 products) segments. For yacht coatings, products containing only an inorganic copper-based biocide as the active compound were the most prevalent in this category, accounting for 70% of all biocidal TBC. In contrast, for the ship segment, the most common biocide profile, found in 70% of products, consisted of a combination of two biocides: inorganic copper paired with a co-biocide. Products used in the ship segment were generally found to incorporate a greater number of biocides in their formulations as compared to the yacht segment, with combinations of up to four biocides in the same product. While five ship products with an inorganic copper-based biocide as the sole biocide were identified, three out of the five products were specifically intended for vessels with aluminum hulls, rather than the more common steel hulls. In comparison, most yacht TBCs (66 out of 95) used only inorganic copper (Cu_2O, CuSCN or copper flakes) as the sole biocide. Another distinction between the two market segments is the lack of biocide-containing FRCs for yachts. Although such products are available for ships (7 products), biocide-free FRCs are nonetheless more common in this segment (10 ship products). This could be due to the technical challenges related to the incorporation of biocides which were only resolved in recent year (Lagerström et al., 2022).

Biocide-free FRCs account for small shares of the market representing only 9.6% and 3.7% of the total products in the ship and yacht segments, respectively. The lower number of FRCs available for the yacht segment could be explained by application challenges for non-professional users, as FRCs are mostly two-components products requiring professional application. One-component products specifically developed for the yacht segment have only been launched in more recent years (Hempel, 2025). The relatively high initial costs of FRCs may also hinder their broader adoption in both segments (Kim et al., 2025). Additionally, most biocide-free FRCs are relatively soft and prone to mechanical damage, which can compromise the coating performance and lifespan (Hu et al., 2020). However, recent studies have demonstrated that biocide-free FRCs can have equal or superior efficacy in comparison to copper-based ship coatings (Lagerström et al., 2022; Oliveira and Granhag, 2020). FRCs have also found to be more sustainable than copper-based ship coatings for operators in terms of costs (Kim et al., 2025). Moreover, environmental regulations on biocidal coatings have become stricter over the years. The HELCOM Baltic Sea Action Plan 2021 has set goals to reduce hazardous substances from biocidal AF coatings to restore and protect the Baltic Sea ecosystem (HELCOM, 2021). Several European countries also have national or regional regulations restricting the use of biocides in antifouling paints, especially in sensitive areas like freshwater bodies and inland waters. For example, in Denmark, pleasure boats that sail in freshwater are not allowed to use biocidal paints (The Danish Environmental Protection Agency, 2025). The Finnish Safety and Chemicals Agency (Tukes) has also implemented strict requirements from several aspects to which antifouling products must comply whereby including restrictions on the use of biocidal coatings in freshwater and inland waters (Tukes, 2025). Therefore, the demand for biocide-free antifouling strategies such as biocide-free FRCs by European boat owners may grow.

For the ship segment, all identified biocide-free TBCs were epoxy-based ice breaking coatings. Meanwhile, the biocide-free TBCs in the yacht segment were found to be more diverse in terms of their binder technology with products utilizing, for example, hydrogel infused

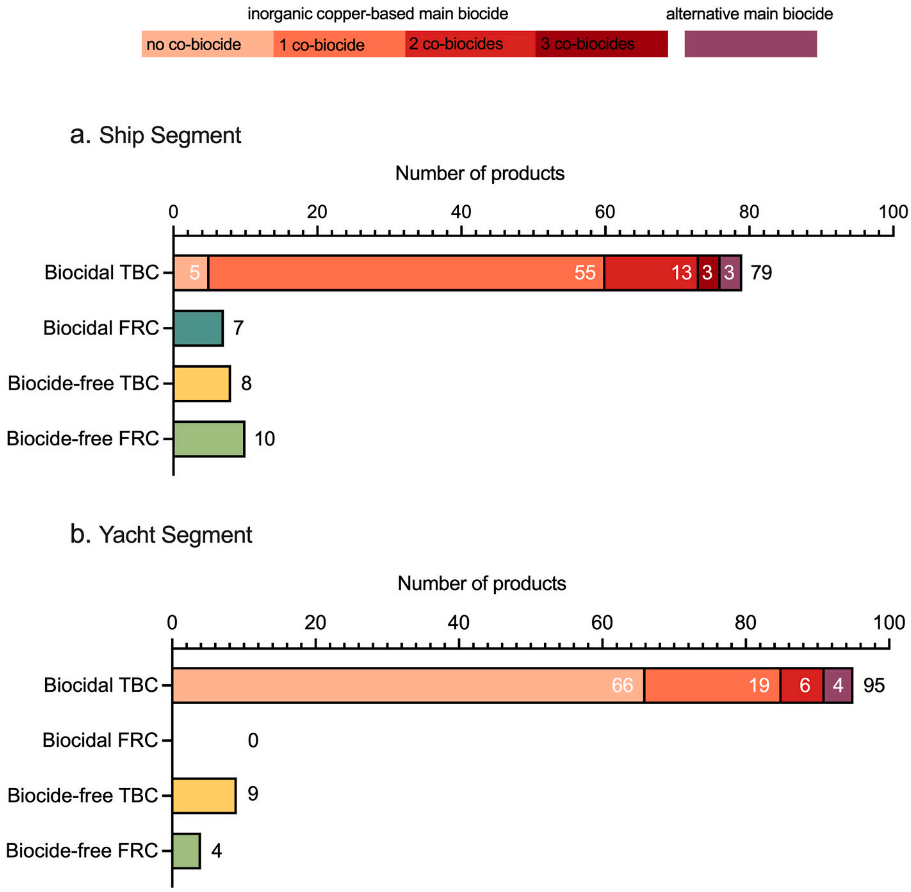


Fig. 4. Number of products in the four identified coating categories for the ship (a) and yacht (b) segments. Note: TBC: traditional binder coating. FRC: foul-release coating.

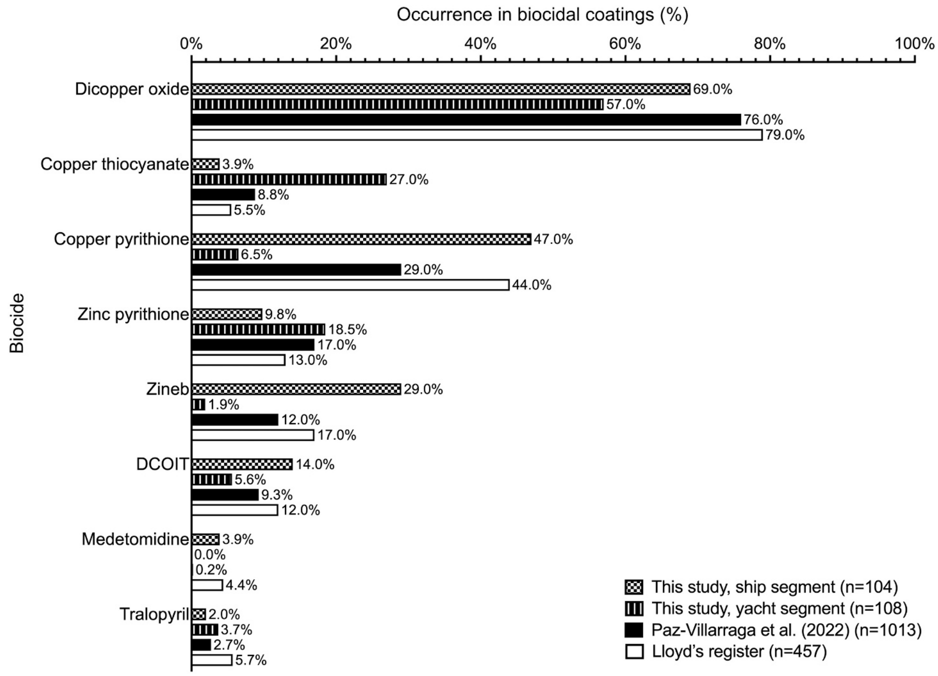


Fig. 5. Frequency of occurrence of biocides in yacht and ship coatings. Note: The data from Paz-Villarraga et al. (2022) was not filtered for duplicates (Voulvoulis, 2006), as opposed to the Lloyd's Register data (sourced in 2025). These products include both ship and yacht segments. Copper flakes, not included in the figure, were only found in the green-colored version of one product, and its concentration is <1%. It was not found in the other two references. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

acrylic film, erodible resins or epoxy. These products are mostly for racing and yachts operating in regulated areas where the use of biocides is prohibited. The greater diversity observed among yacht coatings could be due to the difference of their operating areas, service time, maintenance frequency and regulatory requirement.

3.2. *Frequency of occurrence and concentration of biocides*

Nine biocides were identified in the coating formulations investigated in this study: Cu_2O, copper pyrithione (CuPT), copper thiocyanate (CuSCN), zineb, zinc pyrithione (ZnPT), DCOIT, tralopyril, medetomidine and copper flakes (listed in descending order of frequency of occurrence in all products). Main biocides consisting of inorganic copper substances (Cu_2O and CuSCN) were the most frequently found in the biocidal products of both segments, with Cu_2O as the most prevalent, presenting in 69% of the ship products and 57% of the yacht products (Fig. 5). However, the total concentration range of inorganic copper-based biocides (Cu_2O or CuSCN) in the yacht segment (5.0% to 47.4 wt%) was found to be somewhat wider than that for the ship segment (16.0% to 49.9 wt%) (Table 2). The wider range observed for the yacht segment could be attributed to the regulatory differences between the two segments. Yacht products with high copper release rates are restricted in some sea regions with lower salinity and lower fouling pressure in the EU (e.g. Swedish East coast and Finland), explaining the occurrence of lower copper content products (Tukes, 2025; KEMI, 2025). Another difference between the two sectors is that CuSCN was present in a small proportion of biocidal ship coatings ($<4\%$), whereas it was considerably more prevalent in yacht coatings (27%). This preference could partly reflect aesthetic considerations, as CuSCN enables the formulation of lighter-colored paints which are more favored by yacht owners (Dürr and Watson, 2009). Furthermore, CuSCN is compatible with aluminum hulls because it does not induce galvanic corrosion, unlike copper-based compounds, making it a preferred choice for vessels constructed from aluminum alloys which is more common for yachts than ships (Finnie and Williams, 2009).

Metal pyrithiones are the most frequently used co-biocides for both segments. However, while CuPT is the preferred co-biocide for the ship segment (47.1% of biocidal products), the yacht segment is more prone to incorporate ZnPT in its formulations (18.5% of products). Additionally, all the biocidal FRCs in the ship segment use metal pyrithiones as their active substances, which are particularly effective against soft fouling organisms (Turley et al., 2005). Both ZnPT and CuPT are currently under evaluation for renewed approval in the EU (Fig. 1). Should they not be granted, the use of the other most frequently detected co-biocides, zineb (29% of products) and DCOIT (14%), may increase in ship coatings. Notably, DCOIT was found in the formulation of six white-colored yacht products of one company, despite regulatory recommendations against its use in yacht coatings (Regulation (EU) No 528/2012).

A few biocidal TBCs were found to use copper-free biocides like tralopyril and medetomidine. The tralopyril-based coatings only make up a small portion of the segment (two ship products and four yacht products) and were all co-formulated with ZnPT. Hence, the pending approval of ZnPT could affect the formulation of tralopyril-based coatings and manufacturers may need to seek a potential replacement. Only four products, all intended for ships, were found to contain medetomidine, of which two also contained an inorganic copper biocide.

The use of biocides in AF products has shown consistent patterns across datasets. Inorganic copper-based biocides were the most frequently used, metal pyrithiones were the predominant co-biocides, while tralopyril and medetomidine were the least used. Analysis of 25 biocides registered for commercial use in antifouling formulations across six countries identified the same trends (Paz-Villarraga et al., 2022). Meanwhile, data collected from Lloyd's Register, covering products from 16 countries, also confirmed the same biocides usage (Fig. 5). This alignment across datasets highlights the global dominance of copper-based biocides and the widespread use of pyrithiones as co-biocides.

3.3. *Product Hazard Potential and influence of biocidal profile*

The PHP-values varied across the four coating categories. The two biocide-free coating categories generally exhibited the lowest PHP-values, while the biocidal coating categories showed significantly higher hazard potential for both market segments (Fig. 6). All compiled data and calculated PHP-values can be found in the Supplementary material File S1.

A wide range in PHP within the biocidal TBC category was identified, with PHP-values of 21–4800 for the ship segment and 7.0–4000 for the yacht segment. For comparison, PHP-values were derived for coatings containing biocides banned due to their hazard to the marine environment (i.e. TBT and Irgarol). The average PHP of three organotin-based coatings was about 32,000, roughly seven times higher than the most hazardous current product. Meanwhile, the mean PHP of three Irgarol-containing coatings was about 1800, placing them in the upper range of current biocidal products (Fig. 6). This mean was exceeded only by products formulated with tralopyril as the main biocide.

Statistical analysis showed a significant difference in the PHP between biocidal ship and yacht coatings which can be explained by the previously shown results that ship products usually include more biocides than yacht products (Fig. 4). Moreover, the concentration of inorganic copper added in ship products was found to be significantly higher than that in yacht products ($p < 0.001$). The statistical comparison between coating categories showed no significant differences within biocidal and biocide-free coating categories for either segment, suggesting that binder technology was not a significant parameter for a product's inherent hazard. However, the huge range in PHP within the biocidal TBC category indicates that some products may pose considerably lower environmental hazards to the marine ecosystem compared to others within the same category.

Biocides were the primary contributors to the PHP of biocidal products, accounting on average for 94% of the PHP in ship coatings and 69% of the PHP in yacht coatings. Among biocidal topcoats, products

Table 2

Average concentration (*w*/w%) of biocides used in biocidal coatings, segmented by ship and yacht categories.

Reference	Market segment	Cu_2O	CuSCN	CuPT	Zineb	ZnPT	DCOIT	Medetomidine	Tralopyril
This study	Ship	34.9% ± 8.3% ($n = 72$)	19.2% ± 2.7% ($n = 4$)	3.2% ± 2.0% ($n = 48$)	5.6% ± 2.4% ($n = 30$)	1.7% ± 2.8% ($n = 10$)	1.5% ± 0.5% ($n = 14$)	0.1% ± 0.02% (n = 4)	3.6% ± 0.6% ($n = 2$)
This study	Yacht	26. 8% ± 12.0% ($n = 62$)	19.5% ± 4.3% ($n = 29$)	2.9% ± 0.9% (n = 7)	3.5% ± 0.8% (n = 2)	6.5% ± 2.1% ($n = 20$)	1.7% ± 0.1% (n = 6)	–	2.9% ± 1.1% (n = 4)
Paz-Villarraga et al. (2022)	Ship and yacht	35.9% ± 12.8% ($n = 768$)	18.1% ± 8.0% ($n = 89$)	2.9% ± 1.6% ($n = 291$)	5.4% ± 2.0% ($n = 116$)	4.0% ± 5.3% ($n = 168$)	1.9% ± 1.9% ($n = 95$)	NA (n = 2)	5.2% ± 1.8% ($n = 27$)

Note: Values represent mean ± standard deviation. For comparison, data from Paz-Villarraga et al. (2022) are included, which combine ship and yacht products.

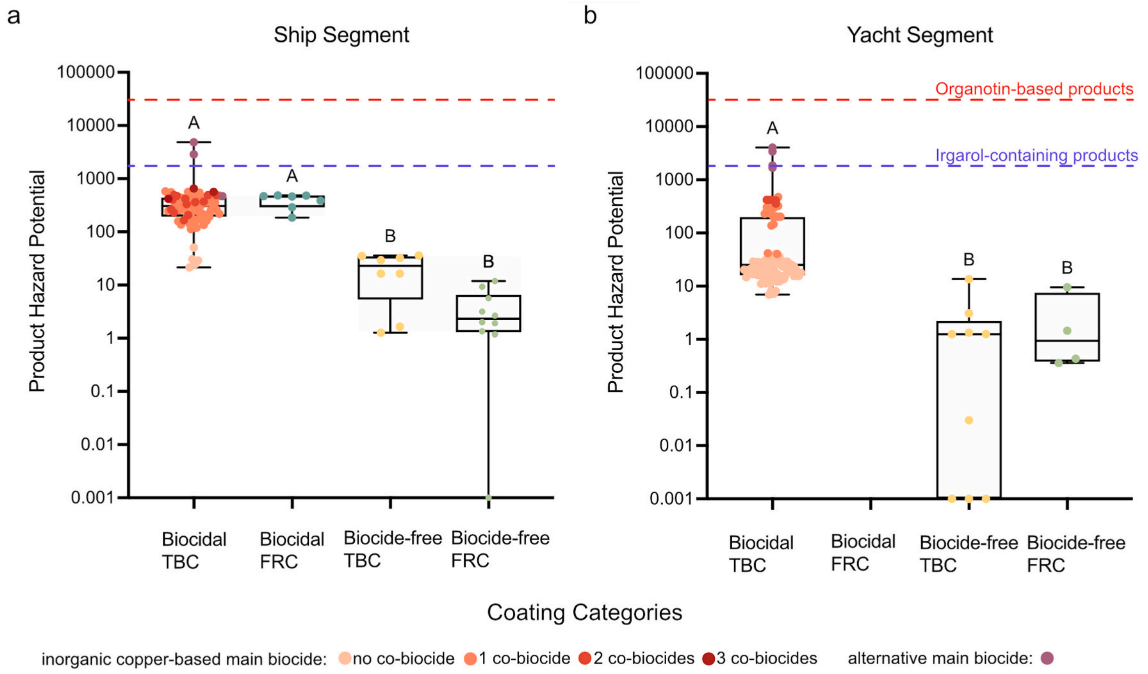


Fig. 6. Product Hazard Potential (PHP) for products in the ship (a) and yacht (b) segments. Note that data has been plotted on a logarithmic y-axis, products with a PHP-value of zero were assigned the value "0.001" for visualization purposes only. Letters above the boxes show the results of the post-hoc testing, where coating categories not connected by the same letter are significantly different. Red and purple dashed lines represent the average PHP of three organotin-based and three irgarol-containing copper-based yacht products, respectively. These are shown for reference as they contain biocides no longer permitted for use under the AFS-convention (Thomas, 2009). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

containing alternative biocides displayed a large variability. In the ship segment, two coatings containing tralopyril had PHP-values of 2900 and 4800, while a third using medetomidine had a PHP of 470. The tralopyril-based coatings were statistical outliers (>95th percentile) and exhibited substantially higher PHP-values than the copper-based coatings. Similarly, in the yacht segment, all biocidal topcoats with alternative biocides contained tralopyril and ZnPT, yielding the highest PHP-values (1700, 1900, 3400 and 4000). The very low PNEC for tralopyril (0.0017 μg/L) explains the high PHP-values. Despite it being added at roughly one-tenth the amount of Cu_2O (Table 2), tralopyril-based coatings can exceed the PHP of copper-based coatings. This highlights that substituting one harmful substance with an even more toxic alternative, even at lower concentrations, may not result in a net environmental benefit. Nonetheless, even when excluding products containing alternative biocides, biocidal coatings were still found to hold significantly higher PHP than biocide-free coatings.

For the inorganic copper-based products, the linear regression analysis between the PHP and the number of included biocides showed a significant increase in PHP with increasing number of biocides in both ship segment ($R^2 = 0.26, p < 0.001$) and yacht segment ($R^2 = 0.87$, $p < 0.001$). The concentration of copper was not found to be significantly lower with the addition of co-biocides for either segment. Therefore, incorporating additional biocides amplifies the cumulative hazard.

3.4. *Chemicals other than biocides contributing to product hazard*

Apart from biocides, 12 chemicals were found to contribute substantially to the PHP-value of coatings, i.e. ≥10% of the PHP of a product after removing any biocide(s) (Table 3). Most of these have already been assessed within the EU and are subject to legal and regulatory measures (Table 3). Moreover, the hazards of each binder technology were found to be driven by distinct sets of contributing chemicals.

For TBCs, additives such as pigments containing heavy metals and plasticizers were found to contribute to the overall hazard profile of coatings. ZnO was found in 74 ship products (all biocidal) and in 97 yacht products, of which two were biocide-free. For biocidal products, ZnO represented 86% of the PHP in the ship segment and 89% in the yacht segment. Meanwhile, it was solely responsible for the PHP of the two biocide-free TBC products in the yacht segment. The hazard of ZnO has also been highlighted in other studies. Karlsson et al. (2010) and Ytreberg et al. (2010) found that leachate water from biocide-free antifouling paints had more pronounced adverse effects in ecotoxicological tests than leachate from traditional Cu-based biocidal coatings due to the excess leaching of Zn (Ytreberg et al., 2010; Karlsson et al., 2010). Zinc and biocides were also identified as major contributors to environmental impact in a life cycle analysis of the global coating industry (Juhl et al., 2024). The same study also highlighted acrylate resins as another key raw material associated with freshwater ecotoxicity. However, in this study, only three acrylate binders were found to be listed in the SDSs, each contributing ≤0.3 *w*/w% to the coating formulations, and they do not contribute substantially to the calculated PHP (Supplementary material File S1).

For the epoxy-based ship coatings, the main driver of the PHP was identified as the bisphenol A (BPA) based epoxy binder. The release of BPA and nonylphenol from biocide-free antifouling paints with epoxy-based binder have been reported in Watermann et al. (2005) (Watermann et al., 2005). BPA has long been the main building block of epoxy resin due to its excellent mechanical strength, chemical resistance and good adhesion, but growing evidence of its toxicity and endocrine-disrupting effects has led to stricter regulations and stimulated more research efforts toward developing BPA-free epoxy alternatives (da Silva et al., 2020; Vermeirssen et al., 2017; Sreehari et al., 2022). These alternatives incorporate bio-based components such as lignin or eugenol to improve sustainability without compromising performance (Laurichesse and Avérous, 2014; Kalita et al., 2021).

For biocide-free FRCs, the potential hazard of the products mainly comes from the copolymers octamethylcyclotetrasiloxane (D4) and decamethylcyclopentasiloxane (D5). Both substances are classified as PBT/vPvB under REACH, with D4 showing very high aquatic toxicity and D5 moderate acute effects but sediment accumulation risks (ECHA,

Table 3

Chemicals other than biocides contributing >10% to the calculated PHP in any product when calculated without biocides, their function in the coating and their regulatory status (ECHA, 2025e).

Coating category	Chemical	CAS number	Function	Market segment	Occurrence in products (n)	Average contribution to PHP (excluding biocides)	Avg Ci/PNEC	REACH regulation
Biocidal TBC	Zinc oxide	1314-13-2	Pigment	Ship	74	86%	5.4	Included in the ERA of biocidal product
				Yacht	95	89%	6.9	
	Reaction Mass Of 3-Methylphenyl Di-4-Methylphenyl Phosphate And 4-Methylphenyl Di-3-Methylphenyl Phosphate And Tris(3-Methylphenyl)Phosphate	1330-78-5	Plasticizer	Ship	5	91%	34	Identified by EU Member State with the concern of having high risk characterization ratios during substance evaluation process by REACH.
				Yacht	5	66%	14	
	Chlorinated paraffins	85,535–85-9	Plasticizer	Ship	4	54%	12	Classified as Substances of Very High Concern (SVHC) under REACH. Listed in Annex XIV (authorization list) and Annex XVII (restriction list) and are partially banned under the POPs Regulation.
				Yacht	8	52%	11	
	Oleic acid, compound with (*Z*)- N-octadec-9-enylpropane-1,3-diamine (2:1)	34,140–91-5	Lubricant	Yacht	16	16%	1.0	It is not undergoing other regulatory evaluations or risk-management activities.
Biocidal FRC	Octamethylcyclotetrasiloxane	556–67-2	Copolymer	Ship	6	95%	0.38	Included in the substance of very high concern (svhc) candidate list of REACH. Listed in Annex XIV (authorization list) and Annex XVII (restriction list)
Biocide-free TBC	Bisphenol A-(epichlorhydrin) epoxy resin MW ≤ 700	1675-54-3	Binder	Ship	4	96%	0.40	Evaluation process by a Member State concluded no regulatory action needed
	Phenol	108–95-2	Binder	Ship	3	37%	1.7	An EU-level harmonized classification and labelling agreed by Member States
	2,2′-dimethyl-4,4′-methylenebis (cyclohexylamine)	6864-37-5	Hardener	Ship	1	93%	1.2	
	Zinc oxide	1314-13-2	Pigment	Yacht	2	100%	7.4	See above
	Oleic acid, compound with (*Z*)- N-octadec-9-enylpropane-1,3-diamine (2:1)	34,140–91-5	Lubricant	Yacht	2	100%	1.3	
	Dipropylene glycol dibenzoate	27,138–31-4	Plasticizer	Yacht	1	92%	2.8	Evaluation process by a Member State concluded no regulatory action needed
	1,2-benzisothiazol-3(2H)-one	2634-33-5	Preservative	Yacht	1	100%	0.03	Under assessment as endocrine disrupting
Biocide-free FRC	Octamethylcyclotetrasiloxane (D4)	556–67-2	Copolymer	Ship	8	33%	0.72	Included in the substance of very high concern (svhc) candidate list of REACH. Listed in Annex XIV (authorization list) and Annex XVII (restriction list)
				Yacht	4	75%	0.65	
	Decamethylcyclopentasiloxane (D5)	541–02-6	Copolymer	Ship	6	70%	2.0	Included in the substance of very high concern (svhc) candidate list of REACH. Listed in Annex XIV (authorization list) and Annex XVII (restriction list)
	Derivative of benzotriazole	104,810–48-2	UV stabilizer	Ship	2	96%	10	Evaluation process by a Member State starts in 2026
				Yacht	1	96%	9.1	

Note: Substance evaluation process under REACH is used to clarify suspicions of risk to human health or the environment. If a Member State concluded no regulatory action needed, it means no potential risk was found regarding all concern endpoints.

2025a). In a study conducted by the German Environmental Protection Agency, cyclic siloxanes such as D4, D5, and D6 were detected as residual monomers at low concentrations in biocide-free FRCs (Daehne et al., 2023; The Danish Environmental Protection, 2024). Although their release through exudation is unintentional and occurs at low levels, effort should be made to reduce the use of these substances due to their persistence and bioaccumulation potential.

3.5. *Limitations and relevance of the PHP*

Even though 89 chemicals were identified after processing the chemical information of the SDSs (Fig. 3, step 1), reliable PNEC values could be sourced for only 44 (Fig. 3, step 2). This limitation was due either to the absence of PNEC values ($n = 25$) or to high uncertainty in the available values ($n = 20$). While these substances were not considered in the calculated PHP, they could still pose a risk to the marine environment. Additional ecotoxicological studies would therefore be valuable to support the derivation of more robust PNECs for these substances and to improve the accuracy of screening-level hazard indicators such as the PHP. For example, organotin compounds, though banned in antifouling paints, are allowed to be added in small amount as catalysts for the curing process of FRCs (IMO, 2005). Four different tin catalysts were found in the curing agent or hardener of 15 different products. Although the leaching tests of tin catalysts have shown undetectable or very low release (The Danish Environmental Protection, 2019), it is still suggested to replace tin catalyst with other less toxic alternatives. More recently, a project has explored the possibility of substituting tin catalysts in FRCs with alternatives such as bismuth carboxylate, titanium-based catalyst or amines co-catalysts, though with varying levels of success (The Danish Environmental Protection, 2019). The project demonstrated that although substituting a key component in a complex system is not a simple swap as it may rather necessitate developing entirely new paint systems, but the technical insights remained critical for developing effective, environmentally sustainable coatings. Furthermore, the chemical inventory compiled in this study offers an overview of chemicals currently in use across different manufacturers, providing a reference list of substances that could serve as potential alternatives.

Another limitation of the PHP approach is that the analysis does not explicitly account for possible curing-related transformation products, and considerations are limited to the parent substances as listed in the SDS. Moreover, it does not consider the release and environmental fate of the chemicals but rather the potential hazards of the dry paint film. Consequently, organic degradable biocides may appear more hazardous under this method than they would if degradation and exposure parameters were accounted for. Therefore, while the PHP approach provides a useful and rapid screening tool, it should be complemented by methods that incorporate release rates, degradation kinetics and ecotoxicity of by-products to achieve a more comprehensive assessment. In future developments, the PHP approach could also be expanded to account for sediment exposure and benthic toxicity as the current method is based on PNECs for pelagic organisms. However, this would require additional ecotoxicological data and fate information for these substances, which are currently limited.

Finally, as the PHP calculation is solely based on the information provided in the SDSs, it may overlook hazardous chemicals that are either exempt from reporting or present as residuals in complex formulations. Because SDSs report only a subset of formulation components, their information should be interpreted with caution and cannot be regarded as a complete hazard inventory. Leachates of FRCs can include unbound silicone oils, PFAS and other unreacted residual chemicals during the polymerization reactions, as the reactions are rarely complete (Lithner et al., 2011; Nendza, 2007). Concerns have been raised regarding the potential physical effects of silicone oils on marine organisms through film-formation on surface sediments leading to their suffocation (Nendza, 2007). However, measurements of silicone oil emissions from coatings and studies on their environmental fate have yet to be conducted (Lagerström et al., 2022; Nendza, 2007). Although no PFASs were declared in the SDSs of any of the studied products, previous findings and information on the manufacturer websites confirm that these can still be contained within coatings. Lagerström et al. (2022) identified silicone-based FRC products with PFAS functionalized PDMS binders (Lagerström et al., 2022), and one was found to still be available on the market within the ship segment in this study. Moreover, at least two biocide-free TBC products in the yacht segment were found to incorporate polytetrafluoroethylene (PTFE, Teflon). PTFE is a type of PFAS, which is highly persistent in the environment and resistant to degradation, raising concerns about their long-term ecological effects and bioaccumulation potential when released (Henry and Timmer, 2025). PTFE-containing products are also considered a major source of microplastic pollution in sediments and benthic organisms (Alaraby et al., 2025).

4. Conclusions

The European marine coatings market offers a wide range of topcoat products, with the majority of options (≥82%) available to ship and yacht owners containing one or more biocides. Among these, Cu_2O was the most frequently used biocide in the >200 products examined, which originated from only six manufacturers. The comparative assessment using the developed PHP calculation revealed substantial variation among biocidal coatings, with PHP-values differing by up to three orders of magnitude depending on their specific biocidal composition. This diversity and number of available coatings can make it challenging for vessel owners to select products with a lower environmental impact. Biocides were found to be the major contributors to the PHP-value of biocide-containing products and coatings using the alternative main biocide of tralopyril exhibited the highest hazard. Moreover, incorporating more co-biocides into an inorganic copper-based coating was found to not generally coincide with a reduction of the copper concentration. Hence, incorporating more co-biocides typically led to a higher PHP. These findings underscore the need for individual product assessments. The assessment also revealed that ship products had a higher hazard potential compared to yacht products as they typically contained more and higher concentrations of biocides.

Beyond biocides, certain chemicals used as binders and additives also contributed to the potential environmental hazard of coatings. While some of these substances are already subject to evaluation by the EU, current biocidal product authorization process focuses exclusively on biocides and ZnO, leaving other hazardous substances outside its scope. Moreover, chemicals known to have adverse impact on the environment, such as PFAS, are not always disclosed in SDSs. Although the present study demonstrated that relevant hazard potential can be derived from existing information, further ecotoxicological studies are needed to improve the robustness of environmental impact thresholds for binders and additives. For many of the identified problematic substances, less toxic alternatives with equivalent functionality are available. Manufacturers should therefore actively reformulate products to minimize the adverse environmental impact of topcoat products.

CRediT authorship contribution statement

Peiyu Hou: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Erik Ytreberg:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Maria Lagerström:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data is provided in the supplementary materials.

Acknowledgements

This study was funded by Trafikverket (Swedish Transport Agency), project number TRV 2023/33687. Maria Lagerström was funded by Formas (reference number 2021-02027).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2026.119799.

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