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Citation for the original published paper (version of record):
Kim, Y., Lagerström, M., Ytreberg, E. et al (2026). Biofouling intensity in European waters: A compiled dataset and spatial assessment with focus
on the Baltic Sea and Northeast Atlantic. Marine Pollution Bulletin, 225.
http://dx.doi.org/10.1016/j.marpolbul.2026.119290

Marine Pollution Bulletin 225 (2026) 119290

Contents lists available at ScienceDirect

Marine Pollution Bulletin

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

Biofouling intensity in European waters: A compiled dataset and spatial assessment with focus on the Baltic Sea and Northeast Atlantic

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ARTICLE INFO

Keywords:
Biofouling intensity
Fouling rating
Port and marina management
Sustainable shipping
Vessel performance
Risk assessment

ABSTRACT

Biofouling on ship hulls increases fuel consumption, greenhouse gas emissions and invasive species spread. For effective management, understanding the expected fouling pressure in the waters of interest is crucial. This study illustrates biofouling intensity by integrating published (2014–2024) and recent field data (2023–2024) from 35 locations across the Baltic Sea, Northeast Atlantic, Mediterranean Sea, and Black Sea. The weighted mean fouling ratings for these sites were assessed together with environmental parameters to identify factors explaining the observed results across different sea basins. Key findings indicate that the Mediterranean Sea sites ($n = 3$) exhibit the highest indicative fouling intensity. A comparative analysis of the data-rich regions revealed that the Northeast Atlantic ($n = 14$) exhibits significantly higher fouling intensity than the Baltic Sea ($n = 17$) when sites with strong estuarine influence are excluded. Salinity was identified as the dominant factor influencing fouling pressure ($R^2 = 0.39 - 0.40$), while dissolved oxygen, phosphate level and temperature showed weaker correlations ($R^2 \leq 0.2$). The presented spatial assessment can be used to manage ship hulls and maritime structures in port or marina areas and provides the first management baseline from existing European data. However, it highlights that the data-poor status of certain regions, alongside other knowledge deficiencies, remains a significant obstacle to unified pan-European management. Addressing these gaps is crucial for establishing a scientific basis for sustainable biofouling practices, in accordance with global initiatives such as the IMO Biofouling Guidelines and the EU Invasive Alien Species Regulation.

1. Introduction

Biofouling on ship hulls and propellers increases hydrodynamic drag, which can lead to higher fuel consumption and operational costs (Yebra et al., 2004). Recent estimates suggest that 7–10% of global shipping fuel consumption and greenhouse gas (GHG) emissions are attributable to biofouling (Kim et al., 2023), exacerbating climate change and amplifying the risk of invasive species spread (Tribou and Swain, 2010; Davidson et al., 2016). In addition, port and marina structures exposed to biofouling can serve as stepping stones or reservoirs for the development and further spread of biofouling (Adams et al., 2014). These impacts highlight the urgent need for effective biofouling management in several maritime operations with the common goal to decrease fuel consumption, maintenance costs and environmental impact.

The most common method for preventing hull fouling is the application of antifouling coatings. Currently, the most widely used antifouling coatings on vessels contain biocides that continuously release harmful substances into the marine ecosystem upon contact with seawater, primarily composed of copper oxide (Lindholdt et al., 2015; Paz-Villarraga et al., 2022). Recent studies focusing on the Baltic Sea indicate that copper-based antifouling coatings account for approximately 33% of the total copper load entering the Baltic Sea (Ytreberg et al., 2022), posing serious threats to human health and marine ecosystems (Ytreberg et al., 2021). Recreational boats that frequently moor in marinas are identified as significant sources of heavy metals in shallow coastal areas (Dafforn et al., 2011), where limited water circulation exacerbates pollutant accumulation in sediments (Biggs and D'Anna, 2012). The contamination of hazardous substances from ships and boats to ports and marinas impacts the local environment. Furthermore, there is a risk that such pollutants may spread to relatively less polluted surrounding areas via currents and sediments due to activities such as dredging (Cappuyns et al., 2006).

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https://doi.org/10.1016/j.marpolbul.2026.119290
Received 17 November 2025; Received in revised form 24 December 2025; Accepted 13 January 2026
Available online 19 January 2026

The environmental and economic impacts of biofouling place an increasing pressure on the maritime industry to implement effective biofouling management strategies (Hopkins et al., 2021). National and regional regulations for biofouling management have been implemented in California, Australia, New Zealand, and Brazil (California State Lands Commission, 2017; Australian Government, 2022; New Zealand Government, 2023; Brazilian Navy, 2025). These frameworks promote pre-arrival hull cleaning to mitigate invasive species transfer and ecological damage. Additionally, internationally, IMO provides biofouling mitigation strategies through implementation of the Biofouling Guidelines (IMO, 2023).

The biofouling pressure, defined as the biofouling accumulation rate (IMO, 2023), is known to vary with environmental parameters, which influence the settlement, growth, and survival of marine organisms. Key factors include temperature, salinity, water flow, pH, dissolved oxygen, and nutrient levels (e.g., nitrates, phosphates) (Nybakken and Bertness, 2005). For instance, temperature and salinity critically affect species distribution and physiological growth rates (Farhat et al., 2016; Lord, 2017; Wrange et al., 2020), water currents influence larval supply and settlement patterns (Radu et al., 2012), nutrient availability impacts growth of phytoplankton and subsequently the food resources for common filter-feeding organisms (Railkin, 2003; Babin et al., 2008; Darvehei et al., 2018), and stable pH levels are important for calcifying organisms (Brown et al., 2018). While the influence of these environmental factors is recognized, biofouling pressure has primarily been investigated in regional studies like Baltic Sea marinas (Wrange et al., 2020) and Mediterranean marinas and ports (Ulman et al., 2019; Tempesti et al., 2020). However, to our knowledge, a large-scale spatial compilation of biofouling intensity across Europe is lacking. Existing research has primarily focused on antifouling efficacy of marine coatings or monitoring of invasive species, while holistic evaluations integrating environmental parameters are scarce. This knowledge gap hinders the development of risk-based and region-specific management strategies, which complicates policy development tailored for Europe's diverse maritime zones.

This study aims to address this issue by conducting the first large-scale spatial assessment of European biofouling intensity, integrating panel immersion tests from 35 distinct locations based on published data from 2014 to 2024 and new data from field tests during 2023–2024. This compilation represents a management baseline derived from the current state of publicly available data. The spatial variability in biofouling intensity, quantified as weighted mean fouling rating is analyzed, and the impact of local environmental conditions on biofouling intensity is assessed. The study aims to provide a quantitative basis for coating developers and ship operators to optimize antifouling practices, while simultaneously highlighting critical data gaps for policymakers. The ultimate goal is to establish a scientific foundation for sustainable, risk-based policies that balance ecological conservation and maritime industry demands.

2. Materials & methods

2.1. Static immersion testing

A literature search for studies assessing biofouling through field tests in European marine waters was conducted by using the databases Google Scholar, Web of Science, Scopus, and ScienceDirect, for combinations of the keywords “biofouling”, “hull fouling”, “fouling communities”, “marine coatings”, “antifouling coatings”, “panel static immersion test”, “field test”, “exposure site”, and “European waters”. The search was performed in December 2024, and the search period was set to the last 10 years (2014–2024).

The initial search results were screened based on titles and abstracts. Subsequently, the most relevant studies were selected based on a set of specific inclusion criteria: 1) the field test was conducted statically in European marine waters; 2) inert control surfaces were used (i.e., uncoated panels or those with non-biocidal primer coatings, explicitly excluding antifouling coatings); 3) exposure duration was approximately six months and critically included the peak summer fouling season to capture maximum biological activity; and 4) sufficient quantitative or qualitative data for fouling assessment were reported. As a result, a total of 42 static immersion tests conducted in European waters, including the Baltic Sea, NorthEast (NE) Atlantic, Mediterranean Sea, and Black Sea, from 10 different sources were identified (Table 1). Additionally, this includes the results of field tests conducted as a part of this study during 2023–2024 at seven port terminals operated by a ro-ro shipping line. See Fig. S1 in the Supplementary material for photos of fouling panels at these locations.

Most of the collected static immersion tests involved PVC panel surfaces applied with primer coatings commonly used for corrosion prevention on ship hulls; in some regions, no coating was applied on the panels (marked with ‘**’ in Table 1). Fouling cover on primer-coated panels can, on average, be approximately 15% higher compared to uncoated panels, as reported by Wrange et al. (2020). Furthermore, there were differences in the color of the panel surfaces used in the examined tests. The color of surface can also affect the degree of biofouling; for instance, Bighiu et al. (2017) found that lighter colored surfaces often acquire less biofouling than darker surfaces.

The assessment of fouling conditions on the panels was primarily based on data from the peak summer season, consistent with the aforementioned selection criterion (criterion 3) for test duration and timing. The site marked with an “*” is included, as it reached the maximum fouling conditions expected during the summer season despite the testing period being limited to three months.

The data pool, comprising 42 tests listed in Table 1, was further refined for the analysis in this study. Tests from 4 duplicated locations (Askö, Kristineberg, Nynäshamn, Tjärnö) were excluded and 3 locations (Pendik, Ghent, Copenhagen) were removed from the dataset as their reported experimental periods did not sufficiently cover the summer season. Consequently, this study utilized data from 35 distinct locations as shown in Fig. 1. Most test sites were situated in coastal regions or river mouths, with the exception of Strängnäs, located in Lake Mälaren. However, this site was included due to the significant roll-on/roll-off transport of trailers and heavy cargo entering from the Baltic Sea to ports in Lake Mälaren. This study categorizes European waters into four marine regions: the Baltic Sea, the NE Atlantic Ocean, the Mediterranean Sea, and the Black Sea, as used in the Marine Strategy Framework Directive (MSFD), which establishes a framework for Community action in the field of marine environmental policy in the Member States of the European Union (EU, 2008). It is important to note that while the datasets for the Baltic Sea and NE Atlantic are relatively substantial, the data for the Mediterranean Sea and the Black Sea are sparse. Therefore, these latter sites are included in this assessment not as representative samples of their entire basins, but as indicative case reports that illustrate the current state of available data.

In this study, environmental parameters influencing biofouling pressure, such as annual average salinity, temperature, pH, dissolved oxygen, nutrients (nitrogen, phosphorus), chlorophyll *a* level, and flow velocity of each field test site, were estimated. These data were sourced from the physical/biogeochemical model products by Copernicus Marine Environment Monitoring Service (CMEMS) (https://marine.copernicus.eu/), which corresponds to the yearly-averaged conditions during the period when the tests were conducted.

2.2. Fouling rating scales

A variety of fouling rating scales have been developed to assess biofouling on panel surfaces. Among these, this paper primarily utilizes three indices: NSTM Fouling Rating (FR) (Navy, 2006), N index (Dobretsov et al., 2014), and fouling index (Wrange et al., 2020). These indices were converted to the weighted fouling rating framework for assessing and comparing biofouling intensity.

Table 1
Summary of static immersion testing of panels in various locations in European waters. '-' symbol indicates that the information was not found in the corresponding source. '*' indicates a site with a test duration of three months, while '**' indicates that no coating was applied on the surface of the panels.

Region	Number of locations	Test period	Exposure depth	Type and color of inert surface	Fouling assessment timing	Fouling rating scale	Reference
Baltic Sea & NE Atlantic Ocean	17 sites	2014.05–2014.10; 2015.05–2015.10; 2016.05–2016.10	≥1 m	Biocide-free underwater paint (PVC panel)/black	End of test	Fouling index	Wrange et al. (2020)
Baltic Sea & NE Atlantic Ocean	4 sites	2018.06–2018.10	~1 m	Underwater primer (PVC panel)/gray	Peak summer season	NSTM FR	Lagerström et al. (2020)
Baltic Sea & NE Atlantic Ocean	3 sites	2020.07–2021.06	1.5±0.5 m	Underwater primer (PVC panel)/aluminum gray	Peak summer season	NSTM FR	Lagerström et al. (2022)
Baltic Sea & NE Atlantic Ocean	3 sites	2023.04–2023.10	0.35–0.95 m	Underwater primer (PVC panel)/gray	Peak summer season	NSTM FR	Lagerström et al. (2025)
NE Atlantic Ocean	4 sites	2016.05–2017.04; 2017.04–2017.09	-	Primer (PVC panel)/ gray	Peak summer season	N index	Finistère 360° (2019)
NE Atlantic Ocean	1 site	2018.05–2019.04	~0.5 m	Primer (PVC panel)/ light gray	Peak summer season	NSTM FR	Oliveira and Granhag (2020)
Mediterranean Sea	1 site	2017.06–2018.01	1 m	Uncoated (PVC panel)	Peak summer season	N index	Gevaux et al. (2019)
Mediterranean Sea	1 site	Summer season (3 months)*	-	Uncoated** (plastic panel)	End of test	Coverage	Castelli et al. (2024)
Black Sea	1 site	2018.09–2020.02	1.17 m	Uncoated** (steel panel)	Peak summer season	NSTM FR	Ozyurt et al. (2023)
Baltic Sea, NE Atlantic Ocean, Mediterranean Sea & Black Sea	7 sites	2023.07–2024.09 (varies by location)	≥1 m	Primer (PVC panel)	Peak summer season	NSTM FR	This study

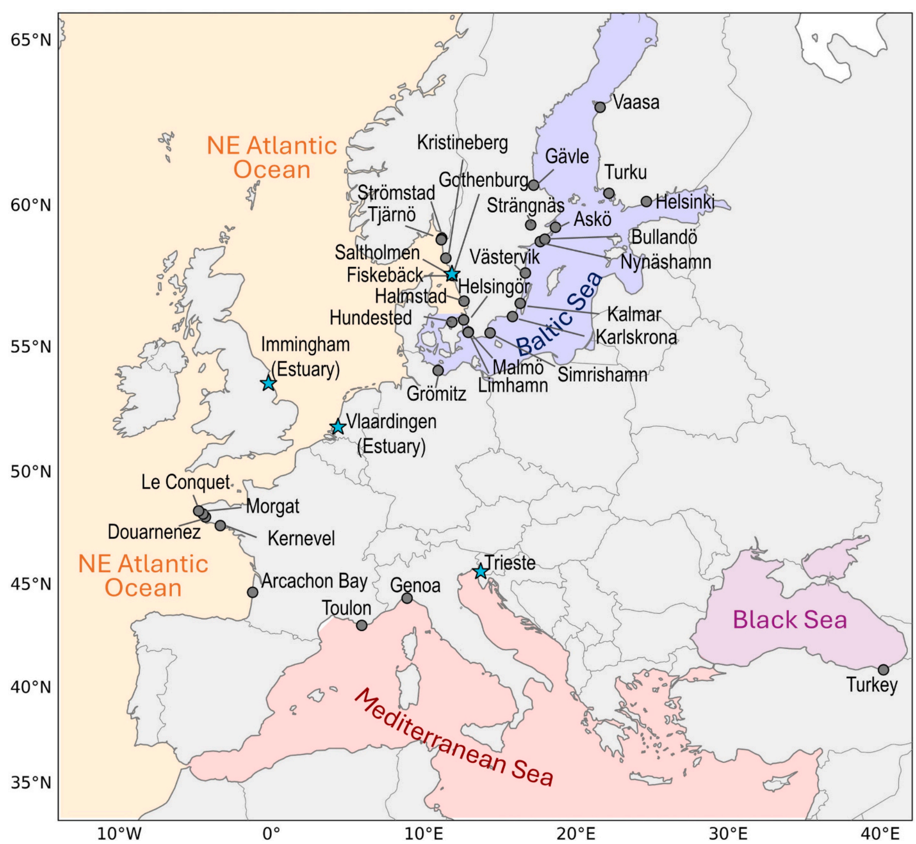

Fig. 1. Static panel immersion tests at 35 locations in European waters used in this study. The dataset is based on the results of a literature search and own field tests conducted in this study (refer to Table 1). Static immersion tests performed in this study are marked with a cyan star. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

While the raw NSTM FR categories are ordinal (0–100), this study utilizes the weighted mean fouling rating (weighted FR) as the primary metric. As described in Eq. (1), the weighted FR integrates the percentage coverage of each fouling type, which provides a continuous variable that reflects the overall severity of biofouling on a panel. The selection of the weighted FR is driven by its correlation with the physical roughness height of the hull, which is essential for predicting frictional resistance and calculating the energy penalty of vessels (Schultz, 2007;

Oliveira et al., 2021).

For datasets reporting single values from other scales, conversions were performed by aligning the described fouling severity with the corresponding NSTM category and assuming 100% coverage to derive an equivalent weighted FR. Although this assumption represents a conservative simplification, it provides a consistent basis for estimating hydrodynamic penalties across diverse data sources. A comparison between the weighted FR and other scales is provided in Fig. S2 in Supplementary material. It was performed by plotting the indices for fouling conditions defined by each scale against equivalent or similar conditions based on the NSTM fouling rating to obtain a linear fitting equation.

The NSTM FR Scale defined by the U.S. Navy serves as the basis for this calculation. It categorizes the ten most common fouling categories (types) in order of increasing severity based on visual inspections (see Table S1 in Supplementary material). Soft fouling, such as algae, slime, and grass, is classified at lower ratings, while more persistent and hard fouling, characterized by calcareous structures, is assigned higher ratings. The weighted FR for the corresponding panel is expressed as Eq. (1).

$$\boldsymbol{Weighted\ FR} = \frac{\mathbf{1}}{\mathbf{100}}\sum\nolimits_{i=1}^{n} (\%\boldsymbol{cover})_i \times (\boldsymbol{fr_{NSTM}})_i \tag{1}$$

Here, n represents the total number of observed fouling types on the panel, $(fr_{NSTM})_i$ is the i-th fouling rating according to the US Naval Ships' Technical Manual, $(\%cover)_i$ is the percentage of the i-th fouling rating covering the panel, and *Weighted FR* is the weighted mean fouling rating of the visually assessed panel.

The increase in roughness is mainly associated with the size and protrusion of fouling organisms with hard shells, such as barnacles. Considering these hydrodynamic penalties, it is important to note that the terms “fouling rating” and “biofouling intensity” used in this study focus on the extent to which the rough and hard characteristics of fouling species impact the hydrodynamic performance of the vessel, as captured by the weighted FR, rather than on the abundance or diversity of the species.

2.3. Statistical analysis

In this study, statistical comparisons were performed to analyze the differences in biofouling intensity (weighted FR) between the data-rich regions: the Baltic Sea ($n = 17$) and the NE Atlantic Ocean ($n = 14$). Data from the Mediterranean Sea ($n = 3$) and the Black Sea ($n = 1$) were excluded from hypothesis testing due to limited sample sizes, although they were retained for visualization and qualitative assessment. A non-parametric Mann-Whitney U test was utilized to compare the weighted FR between the Baltic Sea and the NE Atlantic Ocean. To further investigate the influence of local environmental conditions, a secondary statistical analysis was conducted excluding sites with strong estuarine or freshwater influence (Strängnäs in the Baltic Sea; Immingham and Vlaardingen in the NE Atlantic Ocean) to isolate the differences driven by marine conditions. The level of statistical significance was set at $p < 0.05$.

To compare and visualize the similarities of overall water quality conditions among field test sites, multidimensional scaling (MDS) was used. MDS is a statistical technique used to create a map that represents the proximity between a set of objects as the geometric distance between points in a low-dimensional space (Kruskal and Wish, 1978; Ramsay, 1982). Prior to MDS analysis, environmental data were normalized by z-score transformation to account for differences in scales and units. The main objective of this analysis was to identify groupings of test sites based on their multivariate environmental profiles and to visualize the overall environmental relationships between different marine regions.

In addition, linear regression analyses were performed to assess the influence of the yearly-averaged environmental conditions obtained at each site on the biofouling intensity. Here, each environmental parameter (annual mean salinity, temperature, pH, dissolved oxygen, nitrogen, phosphorus, chlorophyll-a levels, and flow velocity) was treated in a separate regression model as an independent variable, with the weighted FR at that site as the dependent variable. The statistical significance of each regression model was also determined by evaluating the p-value of the slope coefficient. The strength and direction of the linear relationship was assessed using the coefficient of determination (R^2) and the slope of the regression line. Statistical procedures and linear regression analyses were primarily conducted using the Python package statsmodels, and MDS analysis was performed using scikit-learn package.

3. Results & discussion

3.1. Spatial assessment of biofouling intensity

Biofouling intensity (weighted FR) at 35 discrete locations in the European marine regions is visualized in Fig. 2(a), based on the peak fouling condition from the field tests (see Table 1). For visualization of the biofouling intensity by location, macrofouling (sessile fauna and flora) were sorted into four color-coded categories depending on the severity, as shown in Fig. 2(b). For typical examples of fouling found in the ports provided as part of this study, see Fig. S1 in the Supplementary material.

Fig. 3 shows the comparison of weighted FR values between the Baltic Sea and the NE Atlantic Ocean. While the Mediterranean Sea and Black Sea sites are displayed in the spatial map to provide indicative fouling levels, they were excluded from the statistical hypothesis testing due to limited sample sizes ($n = 3$ and $n = 1$, respectively).

When considering all sampling locations in the dataset (solid bars in Fig. 3), the NE Atlantic Ocean showed a higher average weighted FR compared to the Baltic Sea. However, no statistically significant difference was observed between these two data-rich regions at the 0.05 significance level ($p = 0.1036$).

To investigate the true regional differences driven by marine conditions, a secondary analysis was performed excluding sites with strong freshwater or estuarine influence (dotted bars in Fig. 3), specifically Strängnäs in the Baltic Sea, and Immingham and Vlaardingen in the NE Atlantic Ocean. This refinement revealed a statistically significant difference at the 0.05 significance level ($p = 0.0258$), with the NE Atlantic Ocean exhibiting significantly higher fouling pressure than the Baltic Sea.

As illustrated by the error bars representing the 95% confidence interval, there is considerable variability in fouling intensity among locations within each marine region, which indicates that fouling intensity is location-specific. These findings provide insights into the influence of geographical and environmental factors on the biological fouling intensity across diverse marine regions. These inter-regional trends may be related to variations in environmental conditions such as water temperature and salinity.

3.2. Water quality conditions at the field test sites

Fig. 4 shows the average annual water quality conditions at the field test sites. The salinity distribution shows substantial variation across different marine regions. The Baltic Sea is characterized as a basin with brackish water due to freshwater inflows and limited exchange with oceanic water (Lehmann et al., 2022), while the NE Atlantic Ocean, which encompasses the North Sea, exhibits a range of salinity levels influenced by both high-salinity oceanic water and various coastal freshwater sources (van der Molen and Pätsch, 2022). The Black Sea has unique stratification due to its deep basin and low exchange rate (Wakeham et al., 2007), while the Atlantic and Mediterranean, which are fully marine, have high salinity levels (Ivanovic et al., 2014). Notably, the Mediterranean typically has higher salinity due to elevated evaporation rates and limited freshwater input (Skliris et al., 2025).

Average annual temperatures exhibit similar trends to salinity, but

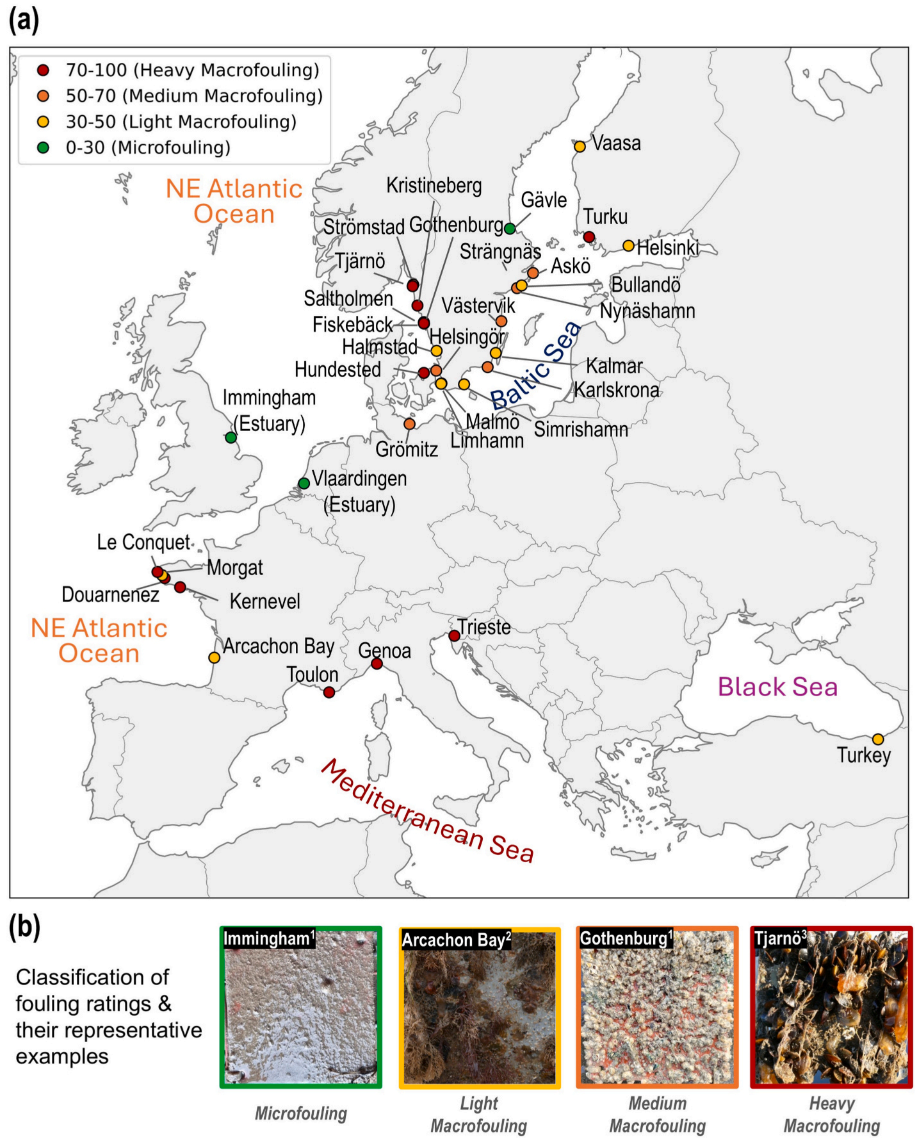

Fig. 2. (a) Biofouling intensity, weighted mean fouling rating, in European waters based on field tests at 35 locations. The markers at each location are color-coded according to their respective fouling rating values, where green indicates microfouling (0–30), yellow light macrofouling (30–50), orange moderate macrofouling (50–70), and red severe macrofouling (70–100), according to the NSTM fouling rating categories used to calculate weighted FR. (b) The classification of fouling ratings used in this assessment and examples of fouling species that can be found in each classification. Photos marked with 1 are sourced from this study, 2 from Lagerström et al. (2025), and 3 from Lagerström et al. (2022). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the differences between regions are generally less pronounced. The Mediterranean experiences higher temperatures due to its geographic location and climatic conditions (García-Monteiro et al., 2022), while the NE Atlantic Ocean and Baltic Sea are influenced by cooler northern waters, resulting in relatively lower average temperatures (Harwood et al., 2008). Other factors, aside from salinity and temperature, tend to show more location-specific trends rather than broad regional patterns.

The water quality conditions at the field test locations are visualized in Fig. 5 using MDS. In this graph, the x-axis (MDS 1) and y-axis (MDS 2) are unitless dimensions, and the distance between samples reflects the environmental similarity between each test site. Overall, samples from the same regions tend to cluster together, which indicates the presence of environmental similarities within these areas. Specifically, the distance between the Baltic Sea and NE Atlantic Ocean clusters is relatively close, and the distances between the Black Sea and Mediterranean clusters are also adjacent. Importantly, some locations, such as Helsingör, Fiskebäck, Immingham, and Vaasa, deviate from their respective clusters. This suggests that these sites have distinct local environmental conditions that differ from the average conditions of their marine areas. For example, sites influenced by significant freshwater inputs or high flow rates, such as Helsingör (located in a narrow strait between Öresund and the Baltic Sea) or Vlaardingen (situated in a long estuarine area), may experience localized impacts that are not typical of the broader marine regions.

3.3. Impact of environmental factors on biofouling intensity

The influence of environmental factors on biofouling intensity for different regions is illustrated in Fig. 6. Among the analyzed environmental factors, salinity is identified as the primary driver influencing fouling intensity in European waters (R^2 = 0.39–0.40). High-salinity regions (33–38 PSU), such as the NE Atlantic Ocean (Kernevel, Douarnenez, Le Conquet) and the Mediterranean Sea (Toulon, Trieste, Genoa), demonstrate relatively high fouling intensity. It can be attributed to the

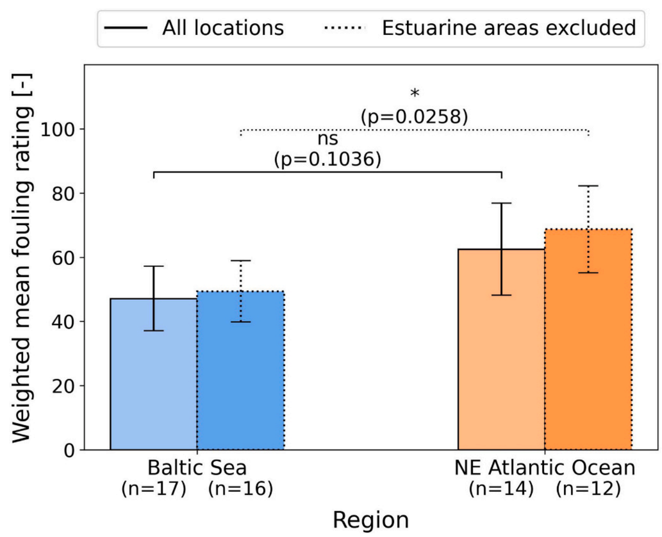

Fig. 3. Comparison of biofouling intensity (weighted FR) between the Baltic Sea and the NE Atlantic Ocean. Solid bars represent the mean intensity for all sampling locations in each region ($\boldsymbol{n} = \mathbf{17}$ for Baltic Sea, $\boldsymbol{n} = \mathbf{14}$ for NE Atlantic). Dotted bars represent the analysis excluding sites with strong estuarine or freshwater influence (Strängnäs in the Baltic Sea; Immingham and Vlaardingen in the NE Atlantic). Error bars indicate the 95% confidence interval (CI). Connecting lines indicate the statistical comparison results (Mann-Whitney *U* test; ns: not significant, *: $\boldsymbol{p} < \mathbf{0.05}$).

proliferation of calcareous organisms such as barnacles and tubeworms. Generally, the marine life thrives under stable osmotic conditions where homeostasis can be maintained without requirement of extra energy (Sundell et al., 2019). On the contrary, low-salinity environments, such as the brackish ports in the Baltic Sea, only allow certain euryhaline species to thrive with the need for constant energy allocation to maintain homeostasis, thereby suppressing fouling intensity (HELCOM, 2018). The brackish Baltic Sea is an area that has low biodiversity and consequently also contain fewer biofouling species (Bonsdorff, 2006).

In addition to salinity, average seawater temperature shows a weak positive correlation with fouling intensity ($R^2 = 0.09–0.13$).

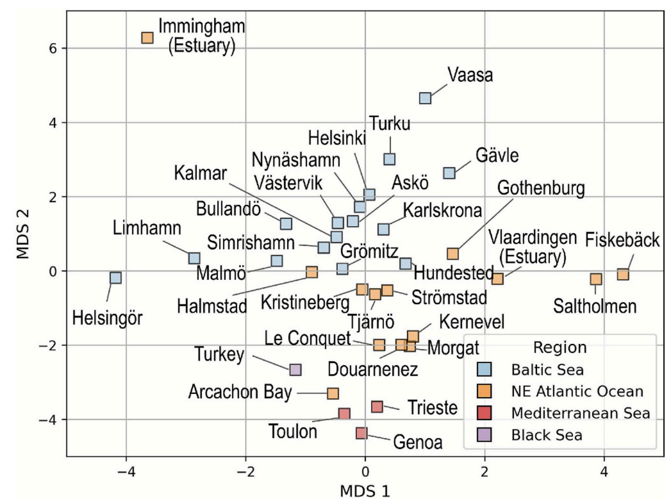

Fig. 5. Multidimensional scaling plot of water quality conditions at field test sites (Strängnäs was excluded from the analysis due to incomplete environmental data; 30 sites from the literature search and 4 sites from the field tests in this study are displayed).

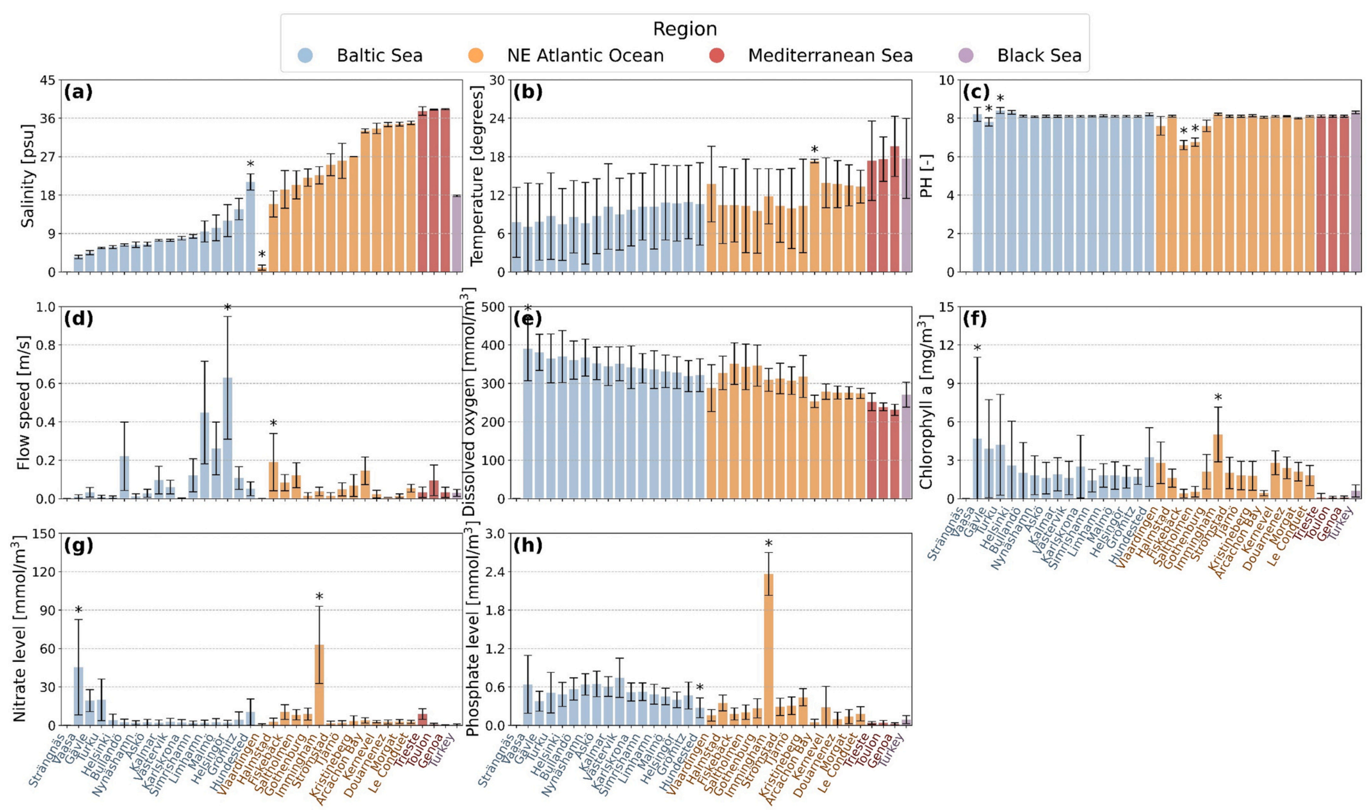

Fig. 4. Average annual water quality conditions at field test sites. An asterisk (*) indicates that the average annual water quality at a given location has a z-score greater than 1.96 (95% confidence interval) compared to the average value for the corresponding region. For Strängnäs, since only salinity and temperature data were available, other parameters are excluded from the graph and z-score calculation.

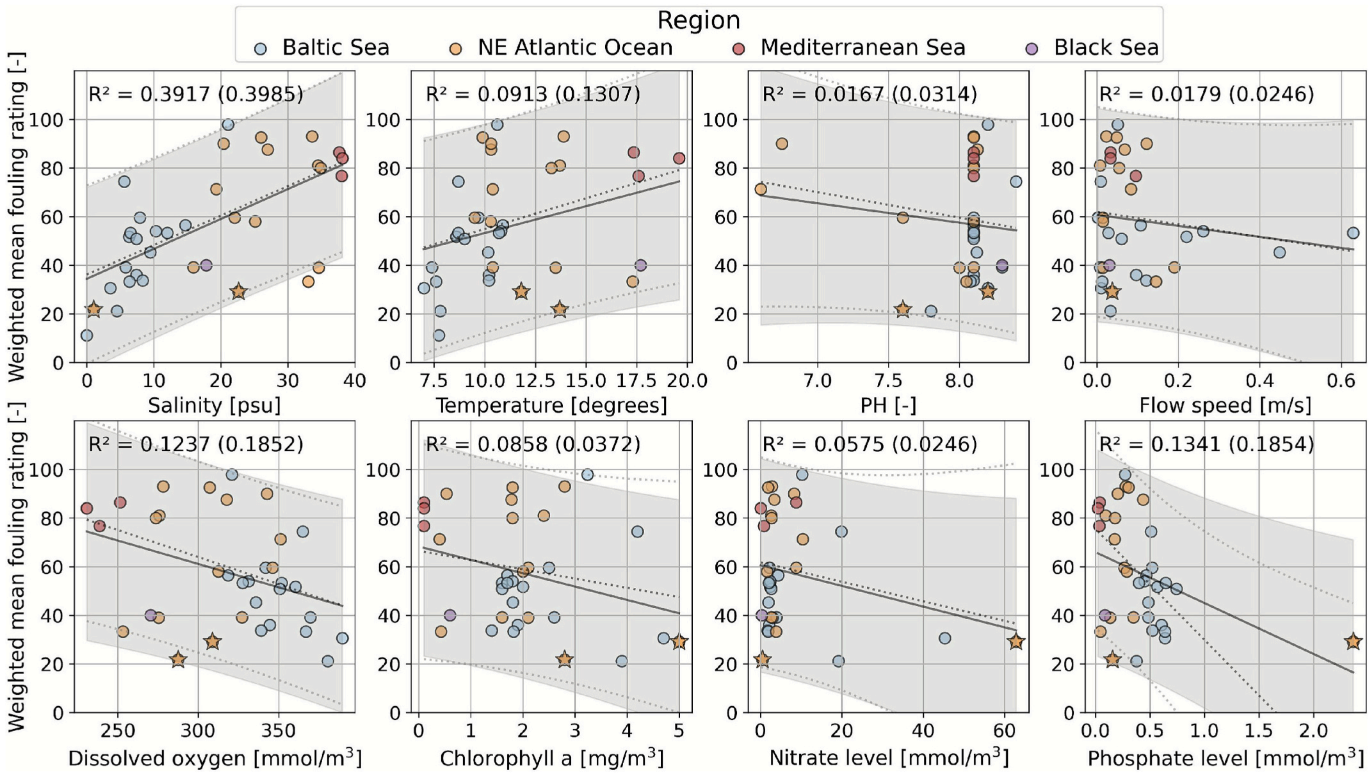

Fig. 6. The influence of environmental factors on biofouling intensity across different regions. This figure presents the relationship between environmental factors, based on annual average values, and biofouling intensity as measured by the weighted FR. A linear regression line with a 95% CI for each environmental factor is depicted, along with the corresponding R^2 scores. The estuarine areas of Immingham and Vlaardingen are indicated with a star (★). Since these estuaries stand out in "green" in Fig. 2, the linear regression lines and 95% CIs for the dataset excluding them are represented by dotted lines, with their respective R^2 scores noted in parentheses.

Mediterranean sites (Toulon: 17.6 °C, Genoa: 19.6 °C) exhibit higher weighted FR values compared to the colder Baltic ports (Vaasa: 7 °C, Gävle: 7.8 °C). While elevated temperatures can enhance metabolic rates and facilitate larval settlement, the low explanatory power here may be due to thermal thresholds and seasonal variability not being fully accounted for (Lord, 2017). For example, summer temperature maxima may surpass optimal ranges for temperate fouling communities, while winter minima impose physiological constraints on the organisms present.

Dissolved oxygen (DO) concentrations are crucial for the survival and growth of marine life, which plays a vital role in promoting biodiversity and maintaining healthy ecosystems (Ekau et al., 2010). In this study, higher mean dissolved oxygen concentrations were associated with lower levels of biofouling (R^2 = 0.12–0.19). This relationship can be attributed to the inverse correlation between dissolved oxygen and temperature, as the solubility of gases decreases with increasing water temperature (Breitburg et al., 2018), and it can also be observed by looking at the aligned trends of annual temperature and dissolved oxygen for each location in Fig. 4. PH levels were found to be slightly basic (pH 8.1) across most locations examined in this study, with minimal discernible effects on fouling intensity within this range. Similarly, the average flow velocity in many locations was predominantly below 0.1 m/s, and it indicates that hydrodynamic factors were not significant contributors to biofouling in the dataset analyzed (R^2<0.03).

Furthermore, algae and phytoplankton grow and reproduce through photosynthesis, and their proper proportions and concentrations are the foundation of supporting marine ecosystems (Railkin, 2003; Darvehei et al., 2018). However, in our analysis, biofouling intensity was found to be weakly negatively correlated with nutrient concentrations (phosphate, R^2 = 0.13–0.19; nitrate, R^2 = 0.02–0.06), and chlorophyll-a levels (R^2 = 0.04–0.09). While it is generally accepted that increased nutrient levels are associated with increased biofouling, this counterintuitive correlation could be due to various factors. In addition to the analyzed nutrients, deficiencies in certain micronutrients, such as silicate or iron, may limit the overall biomass of phytoplankton and result in a lack of food resources available to organisms (Shigenobu, 1998; Schoffman et al., 2016). Moreover, not only the total concentration of nutrients but also their type and bioavailability may have different effects on different biofouling species.

Apart from these causes, it is important to acknowledge potential uncertainties inherent in the environmental data, as this study utilized yearly-averaged conditions from CMEMS model products, which may not fully capture the high spatial-temporal variability of water quality parameters at the specific test sites. The absence of strong correlation with environmental parameters besides salinity and temperature can either be due to a true lack or be dependent on the input data quality. The water quality information obtained from the CMEMS model used to describe the site typically has a spatial resolution on the order of 10 km. To clarify the complex dynamics of ambient environmental effects at a particular site, high-quality, high-resolution data would be needed (for example, through in situ measurements).

Additionally, the individual settings of each field test run, such as the start and duration of the test, treatment of panels, and the assessment method used for the fouling rate, have an impact on the results. The severity of biofouling in this study was quantified using the weighted FR metric derived from NSTM categories. This metric has limitations when used to calculate drag for moving vessels, as it is based on data originating from panels deployed in relatively stagnant water conditions. The increase in drag created by hard biofouling will be dependent on the protrusion of organisms from the hull, while for softer organisms, also their capacity to streamline along a moving hull will impact the resulting drag. Furthermore, the specific attachment strength of the organisms (i.

e., force needed for organism detachment) will be of importance for density of fouling that will be sustained on the hull at different vessel speeds (Oliveira and Granhag, 2016). This inherent difference between static panel data and dynamic hull conditions is another critical reason why the spatial assessment presented in this study should be interpreted as a comparative baseline, rather than a direct predictive tool for fouling on specific moving vessels.

3.4. Management and policy implications of the spatial assessment

The spatial assessment derived from this study could serve as a valuable resource for various stakeholders, including ship operators, port and marina authorities and policymakers (Fig. 7). The regional port authorities can utilize these data to identify biofouling hotspots within their jurisdiction in advance and strategically allocate resources for targeted maintenance. For example, ports identified in high fouling pressure areas can prioritize inspections and implement proactive cleaning schedules on underwater infrastructure. Moreover, the dataset serves as a valuable dataset for assessing which ports face elevated risks concerning the introduction and spread of invasive alien species (IAS). High fouling pressure, as depicted in this work, often correlates with a greater diversity and abundance of organisms that could potentially attach to a hull and be spread to other marine regions. This can highlight ports that may act as significant nodes in IAS dispersal networks. Furthermore, this information is also important for environmental impact assessments (EIA) for new port development or expansion, which allows for informed planning to minimize both biofouling and associated IAS risks.

For commercial ship owners, these findings offer a tool to predict and assess fouling risks along planned voyage routes, which facilitates the implementation of cost-effective operational strategies. As detailed in Section 2.2, a key strength of using the weighted FR lies in its continuous relationship with the physical characteristics determining hull roughness. This connection is significant as increased hull roughness is the primary cause of hydrodynamic drag, which directly leads to higher fuel consumption, GHG emissions, and increased operating costs (Hadžić et al., 2022). Therefore, this analysis is not merely an ecological snapshot but an important tool for managing economic outcomes. By identifying high-pressure zones, operators can better quantify and mitigate financial impacts, such as by optimizing maintenance schedules to reduce overall ship life cycle costs (Koričan et al., 2024). For example, operators of vessels regularly sailing from areas of lower fouling intensity (Baltic Sea ports often indicated as "green") to those with significantly higher fouling pressure (Mediterranean Sea ports indicated as "red"), can use this information to enhance hull condition monitoring and apply proactive management. Such proactive management can involve choosing more specialized antifouling coatings during planned drydocks or adjusting the frequency of in-water hull inspections and cleaning between drydocking intervals. These steps are essential to manage hull roughness, prevent performance losses, and optimize life

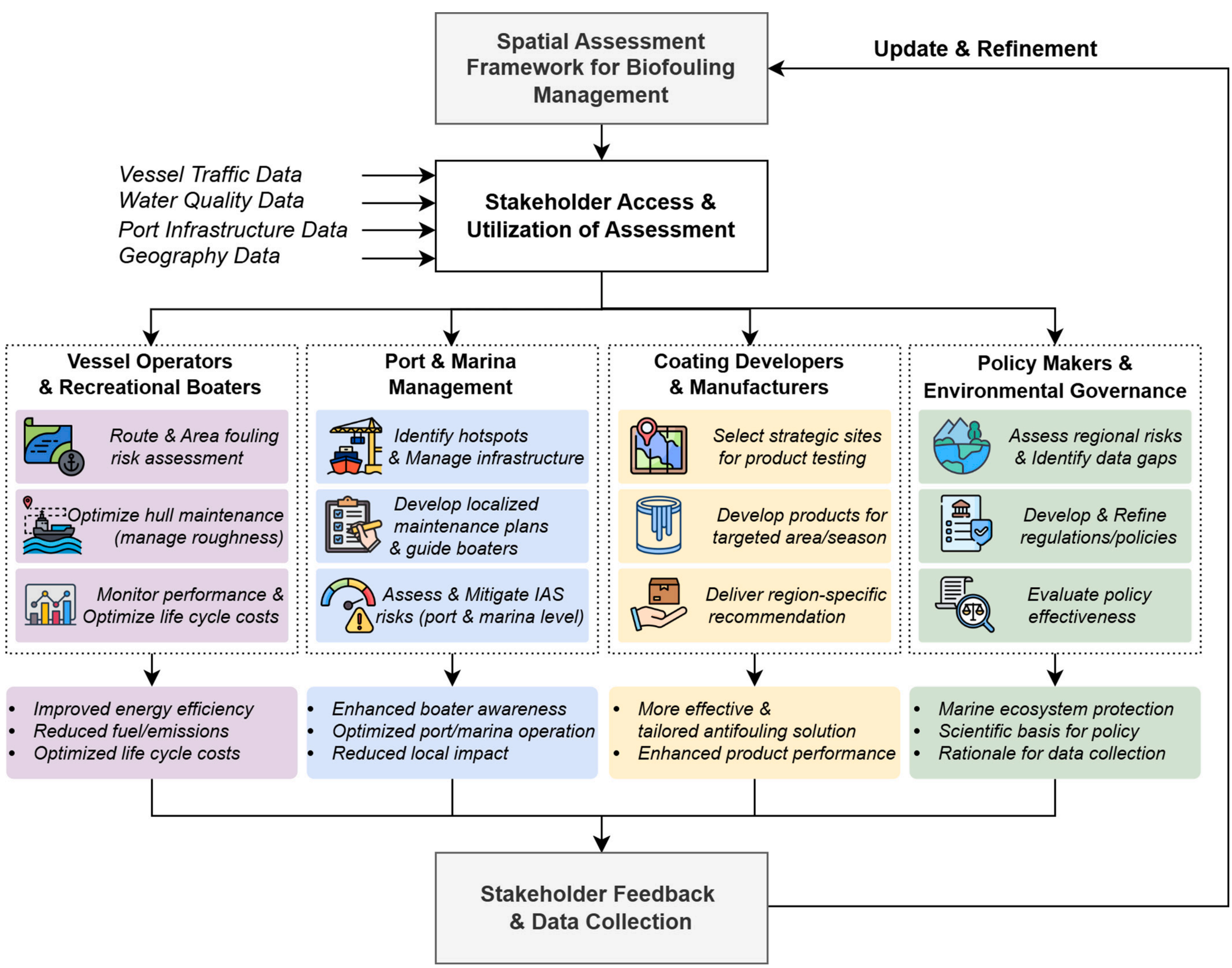

Fig. 7. Conceptual overview on how stakeholders could utilize the spatial assessment of biofouling.

cycle costs (Oliveira et al., 2021; Swain et al., 2022).

This approach is also relevant for the recreational boating sector, which is often characterized by frequent trips within specific coastal and harbour areas and potentially extended periods at mooring (Johansson et al., 2020). Recreational boat owners can use this spatial compilation to understand the specific risks in their area or intended cruising area, especially during peak seasons such as summer, and to help make decisions about appropriate fouling prevention measures such as utilizing in-water brush washing stations scheduling lift-outs and performing hull maintenance (Dahlström et al., 2018).

Furthermore, marina operators can also utilize the developed data baseline to assess the biofouling intensity levels in the areas where their marinas are located and formulate tailored marina maintenance plans to enhance operational efficiency. Providing boat owners with clear guidance on managing hull biofouling can facilitate the adoption of proactive and environmentally responsible hull maintenance strategies, such as selecting appropriate coatings and optimizing cleaning schedules. This approach aligns with the framework proposed by Wrange et al. (2020), which supports sustainable antifouling practices for Baltic Sea boaters through effective fouling monitoring.

Coating developers and manufacturers can also find significant utility in the presented data. With these geographically specific fouling pressure data, developers can optimize new coating formulations for expected fouling levels and design tailored coatings to counter specific fouling communities prevalent in certain regions. This analysis can also inform the selection of strategic locations for field testing of new products. In addition, with this detailed understanding of regional fouling variations, developers can refine their product recommendations and marketing strategies to provide more precise and effective antifouling solutions for the various maritime sectors operating in European waters.

The utility of this study has broad applications that could extend beyond port management, shipping, recreational boating, and coating development to encompass marine environmental management and wider societal benefits. Beyond enhancing operational efficiency, the assessment could serve as a robust scientific basis for informed policy decisions. This includes measures such as strengthening hull inspection protocols in ecologically sensitive areas, implementing hull cleaning regulations in heavily fouled zones, and establishing preventative regulations to mitigate the spread of invasive species. Importantly, this work also highlights the significant data gaps which must be addressed by policymakers to create effective, unified pan-European regulations. The continuous updating and expansion of this data baseline, incorporating long-term monitoring data, will not only refine biofouling management strategies within European waters but also contribute significantly to achieving global sustainability goals in maritime sector, such as those outlined in the IMO's Biofouling Guidelines (IMO, 2023) and the EU's Invasive Alien Species Regulation (EU, 2014).

4. Conclusion

Several earlier works, including both field testing and port monitoring data, have focused on specific environmental and ecological issues in certain geographical areas (i.e., antifouling efficacy in the Baltic Sea from Lagerström et al. (2022) and invasive species in Mediterranean ports from Tempesti et al. (2020)). This study is the first to integrate publicly available datasets with new field test data into a single spatial assessment for European waters. The goal was to illustrate the spatial patterns of biofouling intensity and to analyze the influence of different environmental factors. Through static immersion tests conducted at 35 sites, regional biofouling intensity was estimated based on the biofouling observed during the summer season on uncoated or primer-coated PVC panels.

Our findings show that, on average, the Mediterranean sites exhibit the highest indicative levels of biofouling, followed by the NE Atlantic Ocean and the Baltic Sea. While statistical comparisons were limited for the data-poor Mediterranean region, a focused analysis between the data-rich regions revealed a statistically significant difference in fouling intensity between the NE Atlantic Ocean and the Baltic Sea ($p < 0.05$) when sites with strong estuarine influence were excluded. This spatial variability in fouling intensity was primarily associated with salinity, explaining the higher fouling in more saline areas compared to the brackish Baltic Sea. Other environmental factors showed weaker or negligible correlations.

The spatial assessment developed here offers significant potential as a practical tool for advancing biofouling management in European waters. It helps maritime operators in identifying high-fouling areas and optimizing maintenance, potentially leading to improved efficiency and reduced costs and emissions. Importantly, this assessment also provides valuable data that can inform policymakers, not only by providing a scientific basis for risk-based strategies but also by highlighting the data gaps that hinder unified pan-European regulations.

Building upon this data baseline and its acknowledged limitations, future research should focus on standardized data collection protocols including collection of real time environmental parameters to fill the identified gaps in data-poor regions, as well as studies that bridge the knowledge gap between static panel data and fouling development on dynamic vessel hulls. Additionally, research is needed that links this spatial baseline to economic impact models and policy effectiveness assessments. This will offer scientific evidence to guide effective biofouling management strategies and inform sustainable shipping policies, thereby contributing to both the long-term health of marine ecosystems and the efficiency of global shipping operations.

CRediT authorship contribution statement

Youngrong Kim: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Maria Lagerström:** Writing – review & editing, Methodology, Conceptualization. **Erik Ytreberg:** Writing – review & editing, Project administration, Investigation, Funding acquisition, Conceptualization. **Lena Granhag:** Writing – review & editing, Project administration, Investigation, 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.

Acknowledgements

This study was carried out within the project IP5_2022 HÅLL 2.0 – Demonstration of sustainable ship hull maintenance strategies (2022-2024), funded by the Swedish Transport Administration (Trafikverket) via Lighthouse Swedish Maritime Competence Centre under the “Hållbar sjöfart” program; Youngrong Kim was funded by the Nanyang Technological University Start-up Grant; Maria Lagerström was funded by Formas within the project “Getting to the bottom” (reference number 2021-02027); Erik Ytreberg was funded by the Swedish Transport Administration (grant agreement TRV 2023/33687).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2026.119290.

Data availability

Data will be made available on request.

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