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Original Article

Impact assessment of ship scrubber effluents reveals adverse effects at realistic environmental concentrations—combining a systematic review of whole effluent ecotoxicological studies with dilution modeling

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Abstract

Concerns regarding the potential adverse effects of ship-generated scrubber effluent discharged to the marine environment and the growing number of ecotoxicological experiments have motivated a systematic review of available whole effluent toxicity studies where marine organisms have been exposed to scrubber effluent. All available whole effluent toxicity studies on scrubber effluent exposure were assessed with respect to reliability and relevance, and toxicity metrics including effect concentration and no/lowest observed effect concentration were compiled to determine hazardous concentrations by applying a probabilistic approach. The ecotoxicological impact was assessed by relating the subsequent hazard concentrations, as derived from species sensitivity distribution curves as the potentially affected fraction of species, to estimated environmental concentrations. Environmental concentrations were estimated from previous studies that modeled scrubber effluent dilution or conducted in situ measurement of the dilution of ship-generated waste. The hazardous concentration for 5% of the species was determined at 0.0003%, corresponding to environmentally realistic concentrations. Despite the wide range of confidence limits, the results indicate that the discharge of scrubber effluents, particularly from open loop systems, poses a significant environmental hazard. These findings provide a scientific basis for future risk and impact assessments of scrubber effluents, contributing to the ongoing policy discussion regarding the need to restrict scrubber water discharges.

Keywords: whole effluent toxicity, environmental impact, chemical footprint, species sensitivity distribution, potentially affected fraction

Introduction

Since 2020, when stricter global sulfur regulations entered into force for maritime fuels, an increasing number of ships have installed exhaust gas cleaning systems, commonly known as scrubbers (DNV, 2025; International Maritime Organization [IMO], 2020). Prior to the stricter sulfur regulations, between 70% and 80% of the commercial fleet used cheap residual fuels with high sulfur content, also known as heavy fuel oil (Corbett & Fischbeck, 1997). Instead of switching to more expensive low-sulfur options, ships can reduce the sulfur oxide content in the exhaust to legally compliant levels with a scrubber, spraying the exhaust with (sea)water, allowing the ships to continue to use heavy fuel oil (Lunde Hermansson et al., 2024; Zis et al., 2022). However, the process of the open loop scrubber—the most common scrubber system, with approximately 80% of market share (DNV, 2025)—continuously produces and subsequently discharge large volumes (up to 1,000 m^3/h) of scrubber effluents to the marine environment (Lunde Hermansson et al., 2021; Ytreberg, Åström, & Fridell, 2021). The scrubber effluent is highly acidic and contaminated, with a typical pH of 3 (Karle & Turner, 2007), elevated concentrations of metals and organic combustion products (Lunde Hermansson et al., 2021; Lunde Hermansson, Ytreberg, & Hassellöv, 2025). Several studies on ecotoxicological responses to scrubber effluent exposure report lethal and sublethal

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effects, such as reduced growth, impaired larval development, and increased mortality in marine organisms (e.g., Koski et al., 2017; Picone et al., 2023; Thor et al., 2021). Furthermore, changes in species composition were detected in multispecies experiments investigating the effects of scrubber effluents on communities of zooplankton (Jönander et al., 2023), phytoplankton (Genitsaris et al., 2023; Ytreberg et al., 2019; Ytreberg, Karlberg, et al., 2021), and picoplankton (Genitsaris et al., 2023, 2024). The increasing number of ships equipped with scrubbers, currently exceeding 6,000 globally (DNV, 2025), and the environmental concerns of their use (e.g., Lunde Hermansson, Gustavsson, et al., 2025; Picone et al., 2023; Ytreberg et al., 2022) have led to the questioning of wide-scale use of scrubbers and caused several countries to restrict the use of scrubbers (International Council on Clean Transportation, 2023; Marine Environment Protection Committee [MEPC], 2022b).

Concerns regarding the potential adverse effects of discharged scrubber effluents in the marine environment were raised within the IMO several years before the first scrubbers were installed on ships (e.g., IMO, 1998). The current IMO guidelines on scrubber use, including risk and impact assessment of scrubbers, are mostly focused on compliance with respect to sulfur oxide levels in the exhaust, nitrogen oxides and particle uptake by the scrubber water, and the pH of the effluent (MEPC, 2021, 2022a). For other substances of concern, a limited number (nine metals and 16 polycyclic aromatic hydrocarbons [PAHs]) are typically included in the assessment, where a substance-based approach is applied assessing risk and impact substance by substance (MEPC 2022a). Although substance-based approaches can be helpful when assessing contaminant loads and the cumulative risk and hazard associated with a selection of constituents in scrubber effluent, research shows that the limited focus of the "usual suspects" is insufficient for predicting toxicity (de Vries et al., 2022; Lunde Hermansson, Gustavsson, et al., 2025). Whole effluent toxicity (WET) experiments provide a more comprehensive strategy to assess the total combined toxic effect of all pollutants. The advantages of using WET testing to assess the potential cocktail effects of scrubber effluents have also been raised in the IMO guidelines (MEPC 2022a). The large fraction of unresolved toxicity observed through WET experiments of scrubber effluents highlights the importance of extending the scope of chemical analysis and considering scrubber effluent a toxic complex mixture (Koski et al., 2017; Lunde Hermansson, Gustavsson, et al., 2025; Thor et al., 2021).

The increasing number of WET experiments with scrubber effluent underscores the need for compilation, synthesis, and critical evaluation of available data to better inform decision makers on the risks and impacts associated with continued use of scrubbers. Therefore, the objectives of this article are as follows: (a) to assess all available WET studies on scrubber effluent exposure; (b) to compile reliable and relevant toxicity metrics for scrubber effluent, including effect concentration and no/lowest observed effect concentration (NOEC/LOEC); and (c) to examine the ecotoxicological impact by relating the subsequent hazard concentrations, as the potentially affected fraction of species, to environmental concentrations from dilution estimates. The results presented here will enhance the scientific basis for future risk and impact assessments of scrubber effluents. These findings can contribute to the ongoing policy discussion at the IMO regarding the restriction of discharges of scrubber effluents.

Materials and methods

This study is divided into three parts. The initial phase involved a literature screening of available ecotoxicological studies investigating the effect of scrubber effluent exposure in WET experiments. The screening, including the assessment of reliability and relevance of the reviewed studies, was done in accordance with the framework presented by Nylund et al. (2024). Second, the toxicity metrics from reliable and relevant ecotoxicological experiments were compiled in a meta-analysis assessing the hazardous concentrations of scrubber effluents. For open loop scrubbers, a probabilistic approach was applied, and a selection of toxicity metrics was plotted in a species sensitivity distribution (SSD) curve. Finally, ecotoxicological effects in the environment were estimated by relating the potentially affected fraction of species found in the marine ecosystem, represented by the species in the SSD curve, to the estimated environmental concentrations of scrubber effluent derived from literature values of modeled or measured dilution of ship-generated waste streams.

Literature screening

The literature screening was conducted following the protocol presented by Nylund et al. (2024) based on the structure presented by Hoffmann et al. (2017) and the practical guide proposed by Foo et al. (2021). The review process was broadly consistent with the Reporting Standards for Systematic Evidence Syntheses formulated by the Collaboration for Environmental Evidence (https://environmentalevidence.org/). Specific details on search strings, inclusion criteria, and study descriptions are listed in online supplementary Material A and B.

In brief, the literature search included studies in English from five bibliographic databases and libraries (Web of Science Core Collection, Web of Science Preprint Citation Index, Web of Science ProQuest Dissertations & Theses Citation Index, Scopus Documents, and Scopus preprints), one web-based search engine (Google Scholar), and one organizational document database (IMODOCS; search strings are listed in Table S1 in online supplementary Material A). Initially, all studies were forwarded to further screening, and apparent duplicates were removed. The screening strategy was based on the inclusion criteria of the PECO statement (population, exposure, comparator, outcome; online supplementary material Table S2) and divided into two steps: the title and abstract were screened to remove non-relevant studies, followed by full-text analysis for studies forwarded from the abstract screening (online supplementary material Figure S1). All documents were screened by a principal reviewer, and 10% of randomly selected documents were checked by an additional reviewer. As an additional source of evidence, relevant data from the European Union-funded EMERGE consortium (Evaluation, Control and Mitigation of the Environmental Impacts of Shipping Emissions) were included in the review process, including studies that had not yet been published or made available through the databases and search engines at the time.

Assessment of reliability and relevance

The studies from the full-text screening were further assessed by applying the CRED framework (Criteria for Reporting and Evaluating Ecotoxicity Data; Moermond et al., 2016). The framework was developed to allow for consistent and transparent evaluation of reliability and relevance and to increase the usability of ecotoxicological studies for regulatory purposes (Moermond et al., 2016). Reliability and relevance have been defined (European Chemicals Agency, 2011; Moermond et al., 2016), where *reliability* refers to the intrinsic scientific quality and *relevance* concerns the purpose of the assessment—that is, the appropriateness of the experimental setup for investigating chosen endpoints and evaluating environmental risk (Molander et al., 2015). In this study, the assessment of relevance was initiated at the abstract screening level, following the PECO statement.

Reliability was assessed at the later stages of the literature review. Due to the complex nature of scrubber water and whole effluent exposure versus the conventional single substance testing, alternative considerations to the reliability assessment were given to some of the criteria (online supplementary material Table S3).

The CRED assessments were based on reporting in the main publication, reporting within supporting information, and complementary information through personal communication. When a study included different experiments, each experiment was assessed with respect to reliability and relevance separately; that is, one study could contain experiments that were categorized differently. Experiments were categorized as follows:

- Reliable/relevant without restrictions, where all reliability and relevance criteria are fulfilled.
- Reliable/relevant with restrictions, where not all details are given or there are some minor flaws to the experimental design, but it is assumed that the results are reliable and the values are used as reported.
- Not reliable/relevant, where the study has clear flaws in experimental design or execution.
- Not assignable, where information needed to assess the study is missing.

In addition, mesocosm studies testing environmentally relevant multispecies communities, which fulfill the first or second category, were classified as supporting data, but toxicity metrics were not used in the quantitative hazard assessment. All CRED assessments are provided as supporting information (online supplementary Material C), and the result and motivation for the chosen classification are summarized in the results. The results from studies classified as "as supporting" or "not assignable" are included in the discussion, but less weight is given to the actual toxicity values in the meta-analysis. Studies classified as "not reliable/relevant" are given a brief motivation to why they were not deemed reliable/relevant and were omitted from the meta-analysis and discussion.

Meta-analysis of ecotoxicological data and hazard assessment

For relevant experiments categorized as reliable/relevant with or without restrictions, data were extracted according to the metadata extraction protocol (Nylund et al., 2024). The compiled dataset included the toxicity metrics of scrubber effluent used in the experiments—namely, effect concentrations where 10% or 50% of the individuals tested were affected (EC10 or EC50), as well as LOECs and NOECs. Acute and chronic studies (as defined by the European Chemicals Agency, 2008; European Commission, 2018) were included. The relevant toxicity metrics were then used to assess the hazardous concentrations of scrubber effluent by applying a deterministic or probabilistic approach (Table 1), depending on data availability, in alignment with current guidelines on derivation of threshold values for regulatory purposes (European Chemicals Agency, 2008; European Commission, 2018). In a deterministic approach, the lowest reliable and relevant effect value is appointed as the critical value for which hazard and risk assessments can be based. In a probabilistic approach, all reliable and relevant effect concentrations can be compiled in an SSD curve where the hazardous concentration for 5% (HC5) can be derived and applied as the critical value.

In this study, if fewer than eight taxonomic groups were represented, as determined on a family level, the deterministic approach was applied; if the selected dataset represented eight or more taxonomic groups, a probabilistic approach was applied (Posthuma et al., 2001). The SSD curves were constructed by the maximum likelihood fit to log-normally transformed data (SSD Toolbox Volume 1.1; Center for Computational Toxicology Exposure, 2024). For species where the toxicity metrics represented several endpoints (e.g., fertilization success and larval development), the endpoint with the lowest geometric mean value was used in the construction of the SSD curve.

Several SSD curves were constructed by different input data, where the data were grouped and selected per the reported values (Table 1). Three groups and corresponding derived SSD curves included data of a single type: NOEC/LOEC (Group A), EC10 (Group D), and EC50 (Group E). To increase the number of data points, acute (Group C) and chronic (Group B) toxicity metrics were included in the construction of two additional SSD curves. For these acute and chronic SSD curves, acute toxicity values were converted to chronic and vice versa by applying the conversion factors proposed by Posthuma et al. (2019). For each group (A–E), an HC5 value was derived, and the main analysis and subsequent ecotoxicological impact assessment focused on the groups with the largest number of data points (Groups B and C) and the most conservative curve, adhering to the precautionary principle.

Principal component analysis (PCA; Sartorius, 2025) was used to examine the possibility of pooling ecotoxicological studies with different scrubber effluent origins (i.e., from ship- or laboratory-based scrubbers), assuming that the concentrations of chemical constituents are directly related to the ecotoxicological response. In the PCA, the comparison was based on a selection of scrubber effluent constituents—specifically, 26 variables consisting of eight metals, 16 USEPA PAHs, and two alkylated

Table 1. Inventory of available data points and the selected approach for determining the critical value depending on data selection.

	No.			Conversion	Approach	Critical value
	Taxonomic groups	Species	Data points			
Open loop and laboratory based						
A: Only chronic NOEC/LOEC	10	12	20	No	Probabilistic	HC5
B: Chronic plus converted acute	12	14	23	Yes[a]	Probabilistic	HC5
C: Acute plus converted chronic	12	14	23	Yes[a]	Probabilistic	HC5
D: Only EC10	8	10	13	No	Probabilistic	HC5
E: Only EC50	9	11	29	No	Probabilistic	HC5
Closed loop						
NOEC/LOEC	4	5	6	No	Deterministic	Lowest NOEC/LOEC
EC50	2	2	2	No	Deterministic	Lowest EC50

Note. NOEC/LOEC = no/lowest observed effect concentration; HC5 = hazardous concentration for 5% of species; EC10/EC50 = effect concentration of 10%/50% of the tested species.
[a] In accordance with Posthuma et al. (2019).

naphthalenes (modified from Lunde Hermansson, Ytreberg, & Hassellöv, 2025)—and the available data were grouped as ship-based open loop, ship-based closed loop, or laboratory-based experimental open loop scrubber. All observations of scrubber effluents (open, $n = 317$; closed, $n = 29$; laboratory based, $n = 6$) for the 26 variables were log transformed and preprocessed by unit variance scaling prior to the PCA. Variable concentrations reported as below the limit of detection or not available/applicable were treated as missing values.

Ecotoxicological impact assessment

The ecotoxicological impact of scrubber effluent exposure was assessed by applying an adjusted chemical footprint approach, enabling a coupling between the results from laboratory WET experiments and the potential environmental impact due to discharge of scrubber effluents. The chemical footprint approach quantitatively describes the environmental space (i.e., water volume) needed to dilute the chemical pollution (in this case caused by discharge of scrubber effluents) to levels below a specified threshold value (approach modified from Bjørn et al., 2014; Kosnik et al., 2022; Zijp et al., 2014). In this study, the results from the WET experiments, where the response was determined for percentages of scrubber water, could serve as a proxy for a threshold for chemical pollution from scrubber effluents (as percentage of scrubber water in the environment calculated from the discharge volumes and the available volume in the receiving water). To apply the chemical footprint approach to the discharge of open loop scrubber effluents to the marine environment, the potentially affected fraction of species was assessed by the SSD curves (Fox et al., 2021). The estimated environmental concentrations of open loop scrubber effluent were based on the following:

- A simplified scenario-building exercise where the available seawater dilution volume was calculated by the operation of a single ship and related to a discharge volume of open loop scrubber effluent
- Comparison with previous modeling efforts of dilution of scrubber effluents (Aghito et al., 2025; CLS Brasil, 2024; Japan, 2019; Word et al., 2023; Ytreberg et al., 2023)
- Comparison with previous modeling efforts of other liquid waste streams from ships (Heinen et al., 2003; Katz et al., 2003; Lewis & Riddle, 1989; Loehr et al., 2006; U.S. Environmental Protection Agency, 2002)

For the simplified scenario building, the dilution factor was calculated by dividing the discharged volume of scrubber effluent within a space by the available seawater volume within the same space (*Equation 1*):

$$\frac{1}{\text{dilution factor}} = \frac{\text{discharged volume}}{\text{available volume}} = \frac{Q \times \text{MCR} \times E_L \times t}{\text{length} \times \text{width} \times \text{depth}}, \quad (1)$$

where the available dilution volume was assumed to 10^6 m^3 based on a ship wake length of 1,000 m, a width of 100 m, and a depth of 10 m (Nylund et al., 2021). The discharge volume was estimated by multiplying the discharge flow rate ($Q = 90$ m^3/MWh, where megawatt hour [MWh] is the unit of energy used to describe a ship's power output) by the ship's specific engine load ($E_L = 70\%$ of maximum continuous rate [MCR = 23 MW]) and accounting for the time (t) that it would take for the ship to travel 1 km (i.e., the length) based on a speed of 10 knots (3 min = 0.05 hr).

Results and discussion

Literature screening

A total of 862 studies were identified from bibliographic databases ($n = 146$), back/forward search on key literature ($n = 501$), search engines ($n = 126$), and organizational databases ($n = 90$; online supplementary material Figure S2 and online supplementary Material B). From this, 179 records were immediately removed as they were identified as duplicates. The title and abstract of the remaining 683 records were screened, resulting in 653 being removed and 30 being forwarded to the full-text screening, one of which was not retrieved as full text ($n = 29$). The full-text screening resulted in the exclusion of 11 more reports, as these were not experimental ($n = 3$), not studying marine organisms ($n = 5$), or not including a seawater control ($n = 1$) or they were duplicates of other publications ($n = 2$). Thus, a total of 18 studies from the database and register search were forwarded to the reliability and relevance assessment (online supplementary Material B).

Additional records ($n = 5$) produced within the research project EMERGE were assessed in accordance with CRED (online supplementary material Figure S2 and Table S4). The information from all available publications of a specific experiment was included in the individual reliability and relevance assessments, but the resulting toxicity metrics were extracted from only one of the publications, where peer-reviewed articles were given precedence to reports. The 23 final studies were represented by 12 peer-reviewed articles published in scientific journals (plus one conference paper that was a duplicate with a peer-reviewed paper), two preprints, one PhD thesis, one BSc thesis, and six technical reports (Table 2, online supplementary material Table S4).

Reliability and relevance of experimental studies

The 22 studies from the systematic literature review that were subject to CRED assessment included >50 unique experiments. Of these, none were categorized as "reliable without restrictions," 29 as "reliable with restrictions" (seven were mesocosm studies and thus categorized as supporting data), 11 as "not reliable/relevant," and 11 as "not assignable" (Table 2).

The assessment of the body of evidence (i.e., the experimental results) suggests that, in general, the diversity of the data points strengthens the body of evidence, covering several species and taxa (online supplementary material Table S5). However, consistency is more difficult to assess as there are few experiments conducted with the same species and/or scrubber effluent. Furthermore, when the risk of bias was assessed, no publication bias could be identified, and although no study has been omitted due to funding bias, it should be noted that studies funded by industry or stakeholders with potential monetary interest (e.g., DHI, 2021; Word et al., 2023) were not used in the final assessment as they were classified as "not reliable/relevant" or "not assignable" due to experimental issues or missing information.

Compilation of ecotoxicological data and hazard assessment

The open loop scrubber dataset (including laboratory-based scrubbers) comprises chronic endpoints of 14 species, representing bacteria, microalgae, crustaceans, mollusks, polychaetas, and echinoderms. Based on the log-normal distribution of the largest and most conservative dataset ($n = 23$)—that is, by selecting NOEC/LOEC (including EC50 values converted to NOEC) of the available data (Group B in Table 1)—HC5 equaled 0.0003% with a lower limit of 0.00001% and an upper limit of 0.009% (Figure 1, online supplementary material Table S6). The SSD curve had a

Table 2. Classification of tests within each record according to the CRED method and corresponding terminology.

Reference	Target organisms: endpoints	Classification
Genitsaris et al. (2023)	Mesocosm with phytoplankton and bacterioplankton communities	As supporting
Genitsaris et al. (2024)	Mesocosm with phytoplankton, bacterioplankton, and protozooplankton communities	As supporting
Ji et al. (2023)	*Dunaliella salina*: growth	With restrictions
	Mysidopsis bahia, also known as *Americamysis bahia*: mortality, body weight, body length[a]	With restrictions
	Mugilogobius chulae: mortality, body weight, body length[a]	With restrictions
Jönander et al. (2023)	Mesocosm with mesozooplankton communities; copepods range = 0.2–20 mm	As supporting
Koski et al. (2017)	*Rhodomonas* sp.: growth	Not reliable/relevant[b,c]
	Acartia tonsa: mortality	Not reliable/relevant[b]
	A. tonsa: feeding/reproduction	Not reliable/relevant[a,c]
	A. tonsa: egg mortality	With restrictions
Kourkoutmani et al. (2025)	Mesocosm with metazooplankton communities	As supporting
Monteiro et al. (2024); Ré et al. (2026)	*Sabellaria alveolata*: fertilization, larval development	With restrictions
	Paracentrotus lividus: fertilization, larval development	With restrictions
	Mytilus galloprovincialis: postexposure feeding inhibition	Not assignable[d]
	Artemia sp.: postexposure feeding inhibition	Not assignable[d]
Picone et al. (2023)	*A. fischeri*: bioluminescence	With restrictions
	Phaeodactylum tricornutum: growth	With restrictions
	Dunaliella tertiolecta: growth	With restrictions
	A. tonsa: mortality (adult, egg, and larval), hatching (F0 and F1), larval development (F0 and F1[a]), egg production[a]	With restrictions
	M. galloprovincialis: larval development	With restrictions
Thor et al. (2021)	*Calanus helgolandicus*: mortality (CIII and CV[e]), larval development (CIII)	With restrictions
Ytreberg et al. (2019)	Mesocosm with microplankton communities	As supporting
	Nodularia spumigena: photosynthetic activity, biovolume, primary productivity	Not reliable/relevant[f]
	Melosira cf. arctica: photosynthetic activity, biovolume, primary productivity	Not reliable/relevant[f]
Ytreberg, Karlberg, et al. (2021); Ytreberg, Åström, & Fridell (2021)	Mesocosm with microplankton communities	As supporting
Zapata-Restrepo et al. (2024a, 2024b)	*Tetraselmis suecia*: cell density	With restrictions
	Mytilus edulis: larval development	With restrictions
Zapata-Restrepo and Williams (2025)	*M. edulis*: fertilization, larval development	With restrictions
	Psammechinus miliaris: fertilization, larval development	With restrictions
Chen et al. (2024)	*Strongylocentrotus droebachiensis*: fertilization, larval development	With restrictions
Tavares-Reager (2023)	Mesocosm on natural phytoplankton communities	As supporting
Vartia (2022)	*S. droebachiensis*: survival, growth, larval development	Not reliable/relevant[a,e,g]
Magnusson and Granberg (2022) not overlapping with other published results	*P. lividus*: fertilization, larval development	With restrictions.
	A. tonsa: mortality (adult and larval), larval development, egg production	With restrictions.
	A. fischeri: bioluminescence	With restriction.
	M. edulis: hepasomatic index, byssus strength, cell viability	Not assignable[a,d,g]
	A. fischeri: bioluminescence	Not assignable[a,d,g]
Japan (2019)	*Skeletonema costatum*: growth	With restriction
	Hyale barbicornis: mortality	With restriction
	Oryzias javanicus: mortality	Not reliable/relevant[c]
Word et al. (2023)	*S. costatum*: growth	Not assignable[a,b,d]
	Dendraster excentricus: survival, development	Not assignable[a,b,d]
	A. bahia: survival, growth	Not assignable[a,b,d]
	Menidia beryllina: survival, growth	Not assignable[a,b,d]
DHI (2021)	*Skeletonema* sp.: growth	Not reliable/relevant[h,i,j]
	A. tonsa: mortality	Not reliable/relevant[h,i,j]
	A. tonsa: ELS mortality, hatching, larval development	Not reliable/relevant[h,i,j]
	Dicentrarchus labrax: mortality	Not reliable/relevant[h,i,j,k]
Marin-Enriquez et al. (2023)	*A. fischeri*: bioluminescence	Not assignable[d,h,i]
	P. tricornutum: growth	Not assignable[d,h,i]
	A. tonsa: mortality	Not assignable[d,h,i,l]

Note. For studies that are assigned “not reliable/relevant” or “not assignable,” table notes describe the rationale for the classification. CRED = Criteria for Reporting and Evaluating Ecotoxicity Data; ELS = Early Life Stages.

[a] No dose-response.
[b] Control with only inlet water.
[c] Only one replicate.
[d] Not enough information provided to allow for assessment the reliability/relevance
[e] High mortality in control.
[f] High nitrogen concentrations and increased growth.
[g] Test water origin not described sufficiently
[h] Test water is filtered before exposure.
[i] pH was adjusted.
[j] Sample preparation involved heavy stirring in open environment
[k] Only one exposure concentration.
[l] Salinity adjusted.

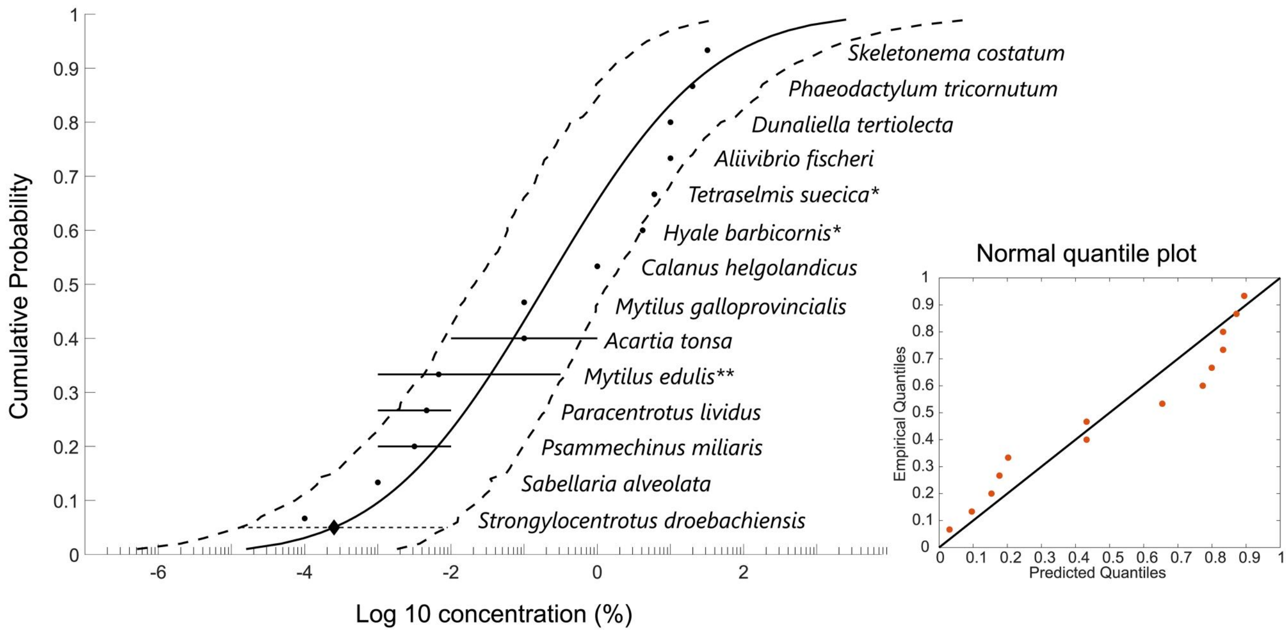

Figure 1. Species sensitivity distribution curve of open loop scrubber exposure from ships and laboratory scrubber based on chronic no observed effect concentrations. *Acute lethal concentration of 50% of the tested species converted to chronic equivalent by multiplying by 1/10. **Chronic effect concentration of 50% of the tested species converted by multiplying by 1/3 (follow the procedure of Posthuma et al., 2019). Hazardous concentration for 5% = 0.0003% (lower level = 0.00001%, upper level = 0.009%). Solid line, log-normal fitted distribution; dashed lines, lower and upper 95% confidence limits.

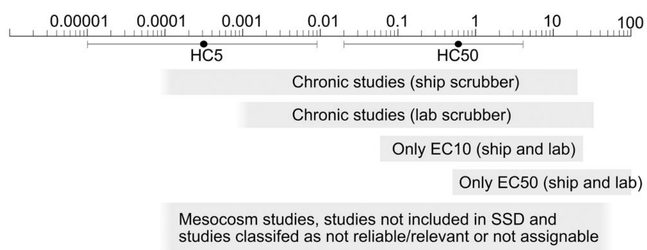

Figure 2. The data range of ecotoxicological effect concentrations of open loop scrubber exposure, including laboratory scrubbers. The range of chronic studies includes the no observed effect concentration, the lowest observed effect concentration (if the lowest tested concentration yields an effect), and the effect concentration of 10% of the tested species (EC10). The acute range includes the effect concentration of 50% of the tested species (EC50). Mesocosm studies are based on no observed effect concentrations, and the range of all effect concentrations from the excluded studies represents that of all available reported effect concentrations. HC5 = hazardous concentration for 5%; HC50 = hazardous concentration for 50%.

weak fit ($p = .09$), as reflected in the large range between lower and upper confidence interval limits, differing almost 3 orders of magnitude. The lowest effect concentration of open loop scrubber effluent exposure (LOEC = 0.0001%, *Strongylocentrotus droebachiensis*) was the lowest tested concentration. In that experiment, an NOEC could not be established (Chen et al., 2024). Likewise, the lowest effect concentrations for *Mytilus edulis* (0.001%) and one of the results from *Paracentrotus lividus* (0.001%) were the lowest tested exposure concentrations of their experiments. Overall, 74% (17 of 23) of the data points had a NOEC/LOEC value ≤1%.

The chronic NOEC and LOEC values from the WET tests ranged from <0.0001% to 20% open loop scrubber effluent (Figures 1 and 2). The large variability is reflected in the upper and lower limits of the derived HC5 and HC50 values, spanning 3 and 2 orders of magnitude, respectively (HC50 = 0.6%; lower limit = 0.02%, upper limit = 1.4%). When only chronic NOEC/LOEC values were included (Group A, Table 1), the SSD curve shifted slightly (HC5 = 0.0001%) with fewer species in the derivation (online supplementary material Figure S3). A large discrepancy was found between the SSD curves when they were derived from either chronic NOEC/LOEC values (Groups A and B; Table 1) or solely EC10 (Group D; online supplementary material Figure S4), where the HC5 value in the latter was >200 times higher than in the former. The acute effect concentrations (EC50) of open loop scrubber effluent ranged between 5% and 60%, and the toxicity values from all the acute and chronic experiments that were not in the SSD curve (including mesocosm) ranged between <0.0001% and >45% (Figure 2).

The use of NOEC versus effect concentrations (ECx) as toxicity metrics in risk assessments and SSD applications has been widely debated (e.g., de Bruijn & Hof, 1997; Fisher & Fox, 2023; Fox & Landis, 2016; Green et al., 2013; Jager, 2011; Warne & van Dam, 2008). The limitation of the NOEC is well documented and discussed (Fisher et al., 2024; Tanaka et al., 2018), where its estimation depends on the experimental design and treatments used, the sample size, the variability in control, and the significance level, with an inherent inability to determine confidence intervals. Nonetheless, in this study, Group B (Table 1) represents the highest number of studies with the most conservative toxicity metrics and is therefore used in the main analysis. From a policy perspective aiming to protect the environment, the toxicity measure from which the SSD is based should represent maximum concentrations with no/negligible effects, potentially making the ECx less fit for purpose (de Bruijn & Hof, 1997; Fisher & Fox, 2023). Most criticism of using NOEC values has been motivated by the risk of underestimating toxicity—that is, type II errors with the incorrect conclusion of no effect when there is an effect (Tanaka et al., 2018). Other toxicity metrics have been proposed (Fisher & Fox, 2023) but could not be applied in this study due to limited data; these include no effect toxicity metrics derived from the concentration–response curve, such as no effect concentration and no significant effect concentration.

In contrast to the results in this work, where a large discrepancy was found between HC5 derived from NOEC versus EC10 values, previous comparisons based on studies with single substances show little difference, varying by a factor of 1.2 (range $= 0.6 - 1.9$; Iwasaki et al., 2015)). There can be several reasons for the large discrepancy between the toxicity metrics, and one important aspect to consider is the inherent complexity of scrubber effluents. Scrubber effluent can be perceived as a black box, with varying chemical composition (concentration of metals, PAHs, and other toxic substances) and properties (e.g., pH; García-Gómez et al., 2024; Gondikas et al., 2025; Lunde Hermansson et al., 2021), potentially affecting multiple toxicological mechanisms and modes of action. The natural variation in species sensitivity and response at different endpoints may also be an important factor. The complexity of scrubber effluent toxicity is evident when the predicted toxicity, based on a substance-specific approach with measured and modeled data, is substantially underestimated when compared with the observed ecotoxicological effects from WET studies (Lunde Hermansson, Gustavsson, et al., 2025). In addition, visual inspection of the SSD curves (Figure 1, online supplementary material Figures S3 and S4), irrespective of the toxicity metric used, suggests bimodality (Fox et al., 2021) where the algae appear less sensitive and the developmental stages of invertebrates more sensitive. The SSD curve from the EC10 values still has a weak fit ($p = .34$), but the confidence interval is narrower, ranging between 1 and almost 2 orders of magnitude, indicating that the use of effect concentrations might reduce the variability of the data. However, six species had LOEC values below the HC5 value derived from the SSD with only the EC10 values (Group D, Table 1; HC5 = 0.07%, online supplementary material Table S6). In the case of WET experiments with open loop scrubber effluents and potentially other complex mixtures, the choice of EC10 or NOEC does affect the SSD curve and its confidence interval, with implications for the assessment of environmental impact and risk (online supplementary material Figure S4). To achieve the largest representation of available data and to align with the precautionary principle, the use of NOEC/LOEC values is considered to be the most appropriate approach for this study.

The PCA of scrubber effluent characteristics (based on concentration of metals, PAHs, and methyl naphthalenes) explained 77% of the variance with four components, including 61% from the first two components. The results from the PCA support the pooling of open loop scrubber effluents from ships and experimental scrubbers (online supplementary material Figure S5). However, the WET experiments using closed loop scrubber effluents had to be separated as the PCA demonstrated a separate cluster. Fewer ecotoxicological data are available for closed loop scrubbers, where only four species are represented (Ji et al., 2023; Thor et al., 2021): the green algae *Dunaliella salina*, the crustaceans *Calanus helolandicus* and *Mysidopsis bahia*, and the fish *Mugilogobius chulae*. The lowest toxicity metric from the closed loop scrubber effluent exposures (LOEC=0.1%) is reported for larval development of *C. helgolandicus* from copepodite stage III to IV (Thor et al., 2021). According to Thor et al. (2021), the lowest tested concentration resulted in adverse effects suggesting that the critical value is probably <0.1%. The potential underestimation of toxicity of closed loop scrubber effluents is also supported by the results of, for example, Marin-Enriquez et al. (2023), confirming higher toxicity of closed loop effluents as compared with open loop effluents from ecotoxicological testing. Due to the limited availability of closed loop scrubber exposure, the potentially affected fraction of species and ecotoxicological impact as chemical footprint were assessed only for the discharge of open loop scrubber effluents.

The results from the WET experiments on single species indicate that the early life stages (i.e., larval development and fertilization success) are the most sensitive to exposure of open loop scrubber effluents. While mesocosm studies of larval stages of mero- and zooplankton did not observe significant adverse effects at scrubber effluent concentrations of 1%, the exposure appeared to result in a dose–response relationship where increased concentration resulted in a lower growth rate (Kourkoutmani et al., 2025). The five most sensitive species identified (Figure 1) belong to sea urchins (echinoderms), mussels (mollusks), and polychaeta (annelids) that are normally not on the list of recommended species for inclusion in a minimum test battery of ecotoxicological experiments for regulatory purposes (see, e.g., European Chemicals Agency, 2008; European Commission, 2018; MEPC 2022a). The high sensitivity of these taxonomic groups underscores their suitability for ecotoxicological assessments, although standardized international protocols for their regulatory use have yet to be established. Similar sensitivity has been observed in WET tests with produced water (i.e., water from oil wells), where the lowest effect concentrations (i.e., highest sensitivity) were observed for mussel (growth inhibition of *M. edulis*), gastropod (larval development of *Haliotis turberculata*), and sea urchin (fertilization of *Strongylocentrotus purpuratus*; Nielsen et al., 2023). This highlights the importance of including a larger test battery when assessing hazards and risk to increase the likelihood of representing the most sensitive species. In addition, several experiments showed significant adverse effects at the lowest tested concentration, which could indicate even higher toxicity (i.e., a lower HC5 value) of the open loop scrubber discharge to sensitive species and life stages. Although more ecotoxicological results could strengthen the body of evidence and provide better knowledge on how discharge of scrubber effluents would affect certain marine organisms, any new data will not change the authoritative evidence that exceptionally low concentrations are already showing adverse effects in several marine species.

The mesocosm studies can be a link between single-species experiments and real-case environmental effects from discharge of scrubber effluents to the marine environment. Community ecotoxicology, integrating the responses of numerous species of taxonomically distinct multidomain natural communities at different levels of biological organization, highlights the complexity of the marine environment and showcases the potential resilience in the marine ecosystem. For example, the distribution of the bacterioplankton community, including diverse taxa, changes in the presence of PAHs, indicating that bacteria may act as a natural degrader of pollutants, potentially reducing toxic effects on other marine organisms (Genitsaris et al., 2025). Complex biological interactions can alter the effects of a pollutant on a single organism (Genitsaris et al., 2025), and the role of bacterial biodegradation could be an important factor when the results of single-species experiments are used to interpret and assess environmental risk and impact. However, given the purpose of risk and impact assessments establishing levels below which no harm is expected, the WET experiments with single species can be considered to represent sensitive conditions with low to no bacterial degradation.

When the derived HC5 value (0.0003%) is applied to calculate the corresponding concentrations of specific substances in diluted open loop scrubber effluents (from existing datasets; e.g., Lunde Hermansson, Ytreberg, & Hassellöv, 2025), their concentrations become very low. For example, by using the geometric mean of known substances' concentrations in scrubber effluent (Lunde Hermansson, Ytreberg, & Hassellöv, 2025) and applying a dilution factor of 300,000 (as needed to reach an HC5 of 0.0003%), the resulting concentrations fall within the range of pico- to femtograms per liter (except vanadium, which remains in the range of nanograms per liter). These levels are in accordance with concentrations reported for PAHs and vanadium in pristine oceanic waters (Bruland & Lohan, 2003; Law et al., 1997), indicating that there can be synergistic effects and/or other, yet to be discovered, substances in scrubber effluent that contribute to the toxic response. This illustrates the challenges in linking substance-based monitoring to actual effects caused by diluted complex mixtures and highlights the importance of applying a WET approach when assessing potential environmental impact.

Ecotoxicological impact assessment

The ecotoxicological impact of the discharge of open loop scrubber effluent was assessed by comparing the estimated environmental concentrations of open loop scrubber effluents with the potentially affected fraction of species, calculated from the SSD curve and derived from single-species laboratory tests. In total, nine studies have estimated environmental concentrations of scrubber effluents or other waste streams from ships (Table 3). The estimated environmental concentrations range between 0.001% and 6%, depending on the assumptions made for the hydrological conditions and the vicinity (spatial and temporal) from the source of discharge.

The results from the impact assessment, including the studies that explicitly modeled the dilution of scrubber effluents (Figure 3), showed that a minimum 10% but up to 80% of the species could be chronically affected by the predicted environmental concentration of scrubber effluents (Figure 3A). The estimated dilution for the simplified scenario from this article was 1:13,800, equivalent to a concentration of 0.007%, resulting in 20% of species being potentially chronically affected (Figure 3A) and 8% being acutely affected (Figure 3B) after a passage of a single ship discharging scrubber effluent. Considering the substantial number of ships that are equipped with scrubbers today and the increasing trend of installations, estimating the dilution based on a single ship passage is not sufficient for assessing ecosystem effects, but the result is an indication of potentially severe effects in areas with higher ship intensity.

The various studies illustrated in Figure 3 utilized different models, measurements, and assumptions to calculate the dilution of scrubber effluents and hence cannot be directly compared. The studies represent near-field analysis (close to ship in time [seconds] and space [meters]) and far-field analysis (further away from ship in time [days] and space [kilometers]; e.g., CLS Brasil, 2024; Japan, 2019), covering scenarios from individual vessels to entire fleets operating over defined spatial and temporal scales (e.g., Ytreberg et al., 2023). For chronic endpoints, most of the predicted environmental concentrations result in a potentially affected fraction of species exceeding 20%, and for acute endpoints, >5% of the species are potentially affected. Assessing the ecotoxicological impact by applying the chemical footprint approach implies that the discharge of open loop scrubber effluents is associated with a substantial hazard for marine organisms. It is worth noting that Japan (2019), Word et al. (2023), and CLS Brasil (2024), presenting the same dilution estimates as in this study, concluded that scrubber water discharge would not pose unacceptable risk. The discrepancy between the previous conclusions of no risk and the substantial hazard shown in this study can partly be attributed to the selection of ecotoxicological data used when deriving critical values or thresholds of scrubber effluent. The most sensitive species identified in this study was not included in the study by Japan and Word et al., who based their assessments solely on their own WET experiments: acute mortality of crustacean *Hyale barbicornis* (NOEC = 12.5%) and biomass of fish *Menidia beryllina* (EC10 = 19.9%). Of the data compiled by CLS Brasil, the most sensitive species was identified as the larval mortality of *Calanus helgolandicus* (NOEC = 1% from Magnusson et al., 2018). Several other studies presented by CLS Brasil overlap the studies reviewed in this work, but none of the most sensitive species and endpoints were captured by the previous works attempting to compare WET measurements with dilution estimates. When all relevant and reliable WET experiments with scrubber effluents are included in the impact assessment, enabling the construction of an SSD curve, the predicted concentrations of diluted scrubber effluents are shown to potentially affect a substantial fraction of species (Figure 3, online supplementary material Figure S6, Table 3). Other studies estimating the dilution of ship waste (dye, particles, and liquid waste) in and around ship wakes show similar results, pointing to notable environmental impacts, as reflected in the potentially affected fraction of species ranging from <1% to 15% (Table 3).

The method and results of the ecotoxicological impact assessment have been inspired by the chemical footprint approach but cannot be considered full implementation of the assessment approach. The assumed occupation of a water volume is theoretical; the environmental fate of the specific chemicals is not accounted for; and the chemical load is not instantaneously diluted into the marine compartment and is often not sufficiently diluted to avoid adverse impacts near their point sources, both stagnant and mobile. However, the theoretical framework of chemical footprints and potentially affected fraction of species provides a methodological approach that couples the laboratory exposure experiments to potential adverse effects, thereby providing essential information to the discussion on the potential ecological impact of scrubber effluents.

Given the large variability between compiled toxicity metrics (Figure 2) and the low HC5 value, which is not protective to the most sensitive species identified so far (Figure 1), a safe level of scrubber effluent concentration in the receiving water could not be determined. As such, from a regulatory perspective, an acceptable risk threshold cannot be established, and it is therefore not possible to perform environmental risk assessments as suggested by the IMO. However, the concept of potentially affected fraction of species, as derived from the SSD curve based on the ecotoxicological response in different species, allowed for a comparison between the compiled ecotoxicological data from this study and the modeled and measured dilution estimates from previous studies (Figure 3, Table 3). Also, recent studies estimating the environmental dilution of scrubber effluents from entire fleets in specified areas (Aghito et al., 2025; Zervakis et al., 2025) showed that the probability calculation of exceeding concentrations of 0.001%, corresponding to a dilution of 1:100,000 and exceeding 10% of the potentially affected fraction of species, occurred 10% of the time in 2018 in the Saronikis Gulf (Zervakis et al., 2025). In the same year, a dilution of 1:1,000,000, corresponding to approximately 3% of the potentially affected fraction of species, occurred 30% of the time in the Saronikis Gulf and 10% of the time in the Northern Adriatic Sea (Zervakis et al., 2025). In large areas of the Baltic Proper, the Öresund Strait, the Great Belt area, and the North Sea, the probability of exceeding a dilution of 1:1,000,000, corresponding to approximately 3% of the potentially

Table 3. Comparison of measured and modeled dilution estimates from scrubber water discharge and other discharges with the PAF of species from chronic and acute SSD curves.

Reference	Dilution (model), %	Description	Model/experimental method	PAF: SSD curve, %	
				Chronic	Acute
This study	0.007	Simple method assuming a dilution volume (1,000 m × 100 m × 10 m) with one model ship (*RoPax*) traveling at 10 knots with a discharge flow rate of 90 m^3/MWh.	Dilution = $\frac{\text{discharged volume}}{\text{available volume}}$	20	8
Japan (2019)	0.01	Model dilution 2 mi after discharge. General merchant ship; 12-knots speed assuming 45 m^3/MWh.	Computational fluid dynamics	22	9
Ytreberg et al. (2023)	0.001–0.01 (large areas within range)	Surface water (5 m) dispersion of open loop scrubber water discharge based on 2018 ship activity in Öresund area; sinking velocity 1 m/day; six-month modeling.	MITgcm model; ship activity data from STEAM	10–22	2–9
Word et al. (2023)	4–6	Model dilution of scrubber water discharged from one ship in Port of Seattle; two tidal scenarios; model extent, 51–57 m along the centerline.	CORMIX (Version 12.0GT) and CORMIX3 hydrodynamic model	78–80	60–65
CLS Brasil (2024)	0.01–0.1 (>1 km, up to 3–4 km, from Source Day 5)	Model dilution of scrubber water discharge from single point (1,300 m^3/day in Port of Tubarão); discharge time set to 15 days and modeling continued for an additional 15 days.	DREAM	22–42	10–24
	0. 1–1 (<1 km from Source Day 5)	Model dilution of scrubber water discharge from single point (1,300 m^3/day in Port of Tubarão); discharge time set to 15 days and modeling continued for an additional 15 days.	DREAM	42–65	24–46
USEPA (2002), Heinen et al. (2003)	0.0005–0.003 (minimum dilution based on maximum concentration in plume)	Measurement campaign tracking discharges (by dye addition and plume tracking) of four cruise ships (9–19 knots) offshore of Miami, Florida.	Measurement campaign	8–15	1–5
	0.0002–0.0004 (average within 10 min from discharge)	Measurement campaign tracking discharges (by dye addition and plume tracking) of four cruise ships (9–19 knots) offshore of Miami, Florida.	Measurement campaign	5–7	~1
Loehr et al. (2006)	0.00002–0.002	Based on equation to estimate dilution factor proposed by Science Advisory Panel. Factor 4 added when compared with field measurements (USEPA, 2002).	Dilution factor = 4 × (ship width × ship draft × ship speed) / volume discharge rate	<1-10	<4
Katz et al. (2003)	0.0002 (particles, paper pulp)	Simulation of near-field dispersion of particles and liquid discharge from U.S. Navy frigate; 8–15 knots; 15 m behind the vessel at 5-m depth.	TBWAKE and field measurements	4	NA
	0.0004 (liquid discharge, dye)	Simulation of near-field dispersion of particles and liquid discharge from U.S. Navy frigate; 8–15 knots; 15 m behind the vessel at 5-m depth.	TBWAKE and field measurements	7	~1
Lewis and Riddle (1989)	0.00001–0.00005	Model dilution in two disposal areas: large area, 13 × 13 km^2, 55-m depth; small area, 5.4 × 9.2 km^2, 15-m depth. Dilution after 48 hr in entire patch area.	Lewis and Riddle (1989)	~1	NA
	0.002	Equation to compute dilution (*D*) in the immediate wake of a ship, also called IMCO formula (Tromp 1976). Use model ship from this study to calculate dilution after 1 hr.	$D = \frac{0.0030 \times U^{1.4} \times L^{1.6} \times t^{0.4}}{Q}$ *U* = ship's speed (m/s); e.g., 20 m/s *L* = ship's length (m); e.g., 200 m t = time from discharge (s); e.g., 3,600 s Q = discharge rate (m^3/s); e.g., 0.4 m^3/s	~12	~4

Note. Chronic SSD curve based on NOEC/LOEC and transformed EC50; acute SSD curve based on EC50 and transformed NOEC/LOEC (Figure 3). PAF = potentially affected fraction; SSD = species sensitivity distribution; NOEC/LOEC = no/lowest observed effect concentration; EC50 = effect concentration of 50% of the tested species; USEPA = U.S. Environmental Protection Agency; NA = not applicable/available.

affected fraction of species, occurred >30% of the time in 2018 (Aghito et al., 2025). The modeling exercises of Zervakis et al. (2025) and Aghito et al. (2025) are based on scrubber water discharge in 2018, when approximately 700 ships were equipped with scrubbers globally, while today >6,000 vessels are operating with a scrubber (DNV, 2025), currently contributing to the cumulative load of scrubber effluent constituents and their subsequent adverse effects in the marine environment.

To conclude, the discharge of scrubber effluents, particularly from open loop systems, poses a significant environmental risk,

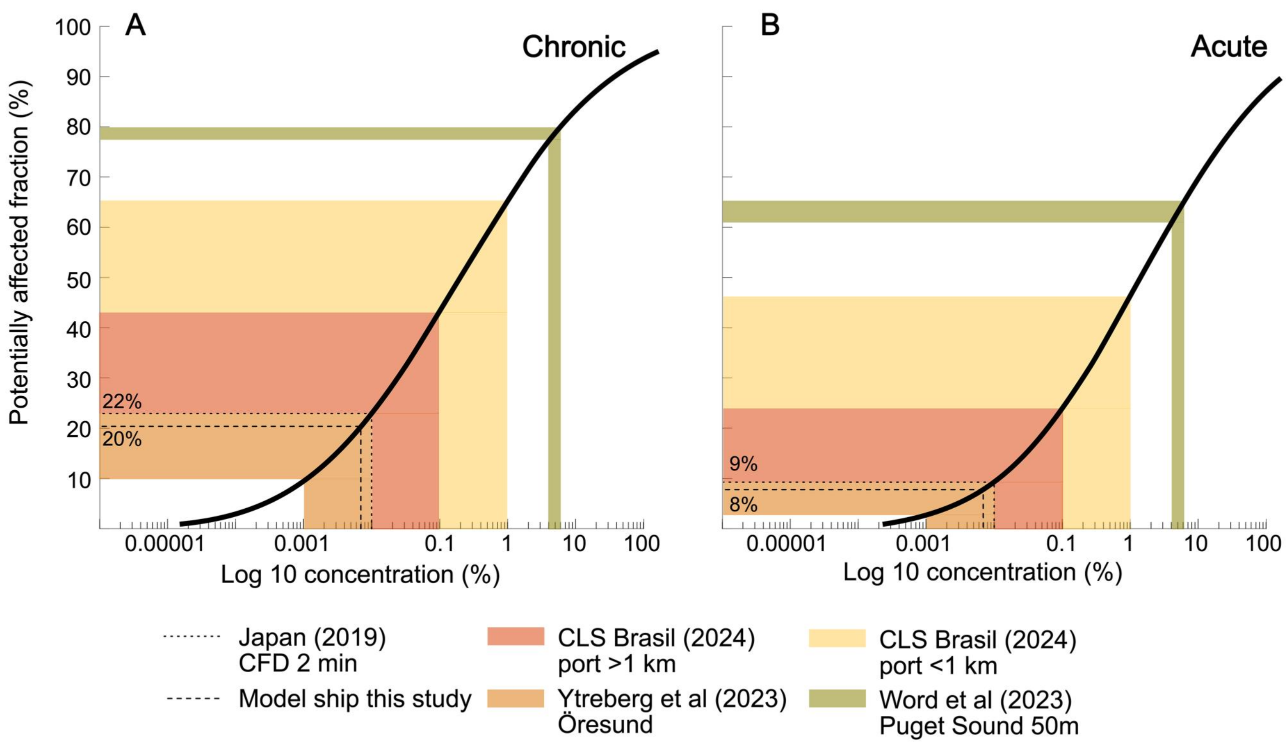

Figure 3. Scrubber water concentrations from dilution modeling results (x-axis) related to the potentially affected fraction of species based on the species sensitivity distribution curve constructed from (A) the chronic NOEC/LOEC values (including the converted EC50; Figure 1) and (B) the acute EC50 (including the converted NOEC/LOEC) from the whole effluent toxicity test. Table 2 lists information about the specific studies and references. EC50 = effect concentration of 50% of the tested species; NOEC/LOEC = no/lowest observed effect concentration.

as supported by evidence from laboratory ecotoxicity tests and chemical footprint estimates. The chronic SSD curve, based on the ecotoxicological experiments of 14 marine species exposed to open loop scrubber effluents, yielded an HC5 value of 0.0003%, equivalent to a dilution of 1:300,000. Comparing the chronic SSD curve with dilution modeling results of open loop scrubber effluent in ports and ship lanes revealed that between 10% and 80% of the species could be chronically affected by the predicted environmental concentration of scrubber water. This study shows that the use of open loop scrubbers poses a risk of negative impact on the marine environment and highlights the importance of including all reliable and relevant ecotoxicological experiments when assessing risk and impact.

Supplementary material

Supplementary material is available online at *Integrated Environmental Assessment and Management*.

Data availability

All data are available in the supplementary material. If more information is required, this will be made available upon request.

Author contributions

Anna Lunde Hermansson (Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing—original draft, Writing—review & editing, Visualization), Amanda T. Nylund (Conceptualization, Data curation, Investigation, Methodology, Writing—review & editing), Ida-Maja Hassellöv (Conceptualization, Funding acquisition, Investigation, Methodology, Writing—review & editing), Nelson Abrantes (Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Writing—review & editing), Ana Ré (Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Writing—review & editing), Chiau Yu Chen (Data curation, Investigation, Methodology, Writing—review & editing), Maria Granberg (Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Writing—review & editing), Kerstin Magnusson (Conceptualization, Funding acquisition, Investigation, Methodology, Writing—review & editing), Marco Picone (Conceptualization, Data curation, Investigation, Methodology, Writing—review & editing), Elisa Giubilato (Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Writing—review & editing), Ian D. Williams (Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Writing—review & editing), Lina M. Zapata-Restrepo (Conceptualization, Data curation, Investigation, Methodology, Writing—review & editing), and Erik Ytreberg (Conceptualization, Funding acquisition, Investigation, Methodology, Writing—review & editing)

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Conflicts of interest

Authors declare no conflict of interest.

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