Systematic review of ecotoxicological studies investigating the effects of scrubber water

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ABSTRACT

The 2020 global limit for sulfur in ship's fuel oil has led to the use of onboard exhaust gas cleaning systems (scrubbers). Scrubbers remove the SO_x from the exhaust gas using a spray of seawater and discharge toxic scrubber wash water directly into the marine environment. There are three types of scrubbers, open-loop, closed-loop, and hybrid scrubbers, where the latter can operate in both open and closed mode. Multiple studies have reported adverse effects of scrubber water on the marine environment, but a systematic review and meta-analysis of existing ecotoxicological results is currently lacking. A review of the effects of scrubber water would be valuable for ongoing national and international discussions on possible restrictions of scrubber water discharge. The aim of this review is to investigate at which concentration adverse effects of scrubber water on the marine environment is expected, for open and closed loop systems respectively, with the review question:

- What is the predicted no effect concentration (PNEC) for open and closed loop scrubber wash water?

The search will include English studies from four bibliographic databases and libraries (Scopus, Web of Science), one web-based search engine (Google Scholar), one organizational document database (IMODOCS), and one source of additional evidence (publications from the EMERGE consortium). The following PECO statement will be used as inclusion criteria:

Population: Any marine species at any life stage
Exposure: Scrubber water of any type
Comparator: Natural seawater
Outcome: Any endpoint

The extracted data and metadata will be quantitative parameters, documented using a custom-made template. The critical appraisal will be made using the Criteria for Reporting and Evaluating ecotoxicity Data (CRED) framework, and the body of evidence will be appraised using authors' judgement and a qualitative scoring system. The data synthesis will include a narrative synthesis of the dataset and a meta-analysis where the most sensitive endpoint from each test-specie will be used to derive a PNEC value for scrubber water.

BACKGROUND

The 2020 global limit for sulfur in fuel oil used on board ships, aiming to reduce atmospheric sulfur oxides (SO_x) emissions has led to the use of exhaust gas cleaning systems (EGCS), commonly known as scrubbers. These systems remove the SO_x from the exhaust gas using a spray of seawater. The resulting scrubber wash water (hereafter referred to as scrubber water) has a low pH ~3 and contains a mixture of metals, polycyclic aromatic hydrocarbons (PAH:s), and particles such as soot (Lunde Hermansson et al. 2021, Thor et al. 2021, Picone et al. 2023). There are three types of scrubbers, open-loop, closed-loop, and hybrid scrubbers, where the latter can operate in both open and closed mode (Turner et al. 2017). Open-loop scrubbers continuously discharge large volumes of contaminated scrubber water (typically ~13,000 m^3 day^{-1} for a medium sized ship of 12MW engine) into the marine environment (Ytreberg et al. 2019), whereas closed-loop scrubbers discharge smaller volumes (126–150 m^3 day^{-1}) of more concentrated scrubber water (Jönander et al. 2023). Multiple studies have reported adverse effects of scrubber water on the marine environment (e.g. Koski et al. (2017), Jönander et al. (2023), Picone et al. (2023), Thor et al. (2021), Ytreberg et al. (2019)), yet, a comprehensive review and meta-analysis of all existing results is currently lacking, as is a review of the quality of available peer-reviewed literature and grey literature. However, such a systematic review would be invaluable for ongoing discussions on possible restrictions of scrubber water discharge, both at global level (e.g. Marine Environment Protection Committee (MEPC) meetings within the International Maritime Organization (IMO) (MEPC 2023, MEPC 2024a, MEPC 2024b)), European level (MEPC 2023, General Secretariat of the Council 2024, ICCT 2023), and national level (e.g. Sweden (SwAM and TS 2022), Denmark (Danish Ministry of Environment 2024)). Therefore, the aim of this review is to derive a Predicted No Effect Concentration (PNEC) value for scrubber water, providing a baseline for discussions regarding concentrations at which adverse effects of scrubber water on the marine environment are expected.

STAKEHOLDER ENGAGEMENT

Stakeholder engagement was conducted within the EMERGE consortium (H2020 EMERGE project, GA n. 874990) and its stakeholders (e.g. The Baltic Marine Environment Protection Commission (HELCOM) and OSPAR Commission). In addition, the author group has extensive experience of stakeholder discussions regarding requirements and perspectives related to scrubber water toxicity assessments (e.g. (MEPC 2020, MEPC 2022, Hassellöv et al. 2020)). Identification of a review outcome useful for policy and industry stakeholders was done based on discussions within the EMERGE consortium before the initiation of the systematic review. The formulation of the review question, aim, and objective was discussed during a meeting on 25 March 2024, where all the EMERGE consortium experts on ecotoxicological studies were invited. The same group further discussed the inclusion/exclusion criteria, search and report protocols, and evaluation criteria during a meeting 28 May 2024 and through a written feedback round before publication of the protocol. No further stakeholder engagement is planned.

OBJECTIVES OF THE REVIEW

The main objective is to review all available literature of ecotoxicological experimental studies using exposure of scrubber water on marine organism/s, evaluate the studies' reliability, relevance, and reproducibility using the Criteria for Reporting and Evaluating ecotoxicity Data (CRED) approach (Moermond et al. 2016), and to derive a PNEC value using all studies CRED-evaluated as "Reliable without restrictions" or "Reliable with restrictions". The PNEC value will be derived following the European Commission (EC) technical guidelines 27 (TGD 27) for deriving Environmental Quality Standards (EQS) (European Commission 2018). Depending on the

number of taxonomic groups (as defined by the TGD 27) represented in the studies fulfilling the CRED criteria, the PNEC value will either be derived using a probabilistic approach (test species from > 8 taxonomic groups) or a deterministic approach (test species from < 8 taxonomic groups. If there are enough studies to fulfil the statistical requirements, a PNEC value will be derived for each of the scrubber types: open loop and closed loop. The review will only include studies where whole effluent testing of scrubber water has been made and will not include studies testing of individual scrubber water constituents.

Research Question

The research question of the literature review is:

- What is the predicted no effect concentration (PNEC) for scrubber wash water?

Definitions of the research question components

A PECO (Population/Exposure/Comparator/Outcome) statement was used to derive search strings and inclusion criteria for the literature review (Foo et al. 2021). Due to the limited amount of ecotoxicological studies exposing marine organisms to scrubber water, and the lack of harmonized terminology, broad definitions were used in the statement.

Population: Any marine species at any life stage

Exposure: Scrubber water of any type (open-loop or closed-loop)

Comparator: Natural seawater

Outcome: Any endpoint

SEARCH STRATEGY

The search will include four 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 (from the repositories arXiv, ChemRxiv, bioRxiv, medRxiv, SSRN, TechRxiv, Research Square). Only documents in English will be included. These databases will ensure coverage of the peer-reviewed literature, pre-prints, and doctoral theses.

To source grey literature and Master's theses, the search will include one web-based search engine (Google Scholar) and one organizational document database (IMODOCS, https://docs.imo.org). The latter is used as the grey literature includes meeting documents submitted for consideration to committee meetings within the IMO, which are archived in the IMODOCS database.

As an additional source of evidence, the members of the EMERGE consortium will be asked to contribute with any relevant data or studies that have not yet been published or made available through the included databases and search engines at the time of the search, but which will be publicly available before the review is published. As the number of ecotoxicological studies with scrubber water is limited, a relatively short time frame is planned for the review (< 6 months), a search update will not be made.

Search options and search strings

The search options, temporal coverage, and search strings to be used for each database/search engine are presented in Table **1**. For the Web of Science (WoS) Core collection search the "All search fields" option will be used (indicated by "ALL" in the search string) and in the WoS preprint

and dissertation searches the "Topic search" alternative (TS) will be used (includes title, abstract, and author keywords). In the Scopus Documents and preprint searches the title-abstract-keyword search option will be used (TITLE-ABS-KEY). The advanced search alternative will be used in all cases except the IMODOCS database search. Furthermore, a backward and forward search will be performed for the key studies in Table **2**, using Scopus.

Table 1. Temporal coverage and search strings for the databases and search engine included in the search.

Search string	Name of search engine/database	Search type	Temporal coverage	Filters used
ALL((scrubber OR "Exhaust gas cleaning system" OR egcs) AND (marine OR harbo*) AND ("wash water" OR washwater OR effluent OR "discharge water" OR "outlet water" OR water) AND (effect* OR tox*))	Web of Science Core collection	Advanced search, All search fields (ALL)	1900–present	English
TS((scrubber OR "Exhaust gas cleaning system" OR egcs) AND (marine OR harbo*) AND ("wash water" OR washwater OR effluent OR "discharge water" OR "outlet water" OR water) AND (effect* OR tox*))	Web of Science Preprint Citation Index and Web of Science ProQuest™ Dissertations & Theses Citation Index	Advanced search, Topic search (TS)	1991–present (Preprint), 1637–present (ProQuest™)	English
TITLE-ABS-KEY((scrubber OR "Exhaust gas cleaning system" OR egcs) AND (marine OR harbo*) AND ("wash water" OR washwater OR effluent OR "discharge water" OR "outlet water" OR water) AND (effect* OR tox*)	Scopus Documents, Scopus Preprints (arXiv, ChemRxiv, bioRxiv, medRxiv, SSRN, TechRxiv, Research Square)	Advanced search, title-abstract-keyword (TITLE-ABS-KEY)	1788–present (Documents), 2017–present (Preprints)	English
With all of the words: marine water effect toxic discharge scrubber concentration PAH "exhaust gas" *Exact phrase*: open loop *At least one of*: egcs effluent	Google Scholar	Advanced search		English
Exhaust gas cleaning system	IMODOCS	Basic search	1998–present	English

Estimating search comprehensiveness

A pre-screening of the literature was conducted using Web of Science and Google Scholar, to identify key references. The documents consider benchmark references that are listed in Table 2, and were selected for being recently published experimental studies of scrubber water exposure, covering a variety of tested endpoints and species. The titles and abstracts from the key references were used to create a word cloud (Figure 1), and search strings were then formulated using the frequently used terms in the word cloud and the PECO statement. In all cases except three (see below), the search strings were piloted and refined through iteration until the search results included all key references and only a limited number of irrelevant results. The three exceptions to this approach were: 1) the Governmental report by Marin-Enriquez et al. (2022) is not peer-reviewed and therefore not included in the WoS or Scopus databases, and was consequently not required to show up when piloting the search terms, 2) similarly, the report by Marin-Enriquez et al. (2022) was not possible to find using Google Scholar (even through a targeted search) and was therefore not required to show up when piloting the search terms, 3) the IMODOCS database does not include all peer-reviewed literature, hence only the key reference known to be included in the IMODOCSs database (Marin-Enriquez et al. 2022) was required to show up in the pilot-search.

Table 2. Key references identified in the pre-screening.

Reference	Type of study
(Koski et al. 2017)	Peer-reviewed article
(Jönander et al. 2023)	Peer-reviewed article
(Thor et al. 2021)	Peer-reviewed article
(Genitsaris et al. 2024)	Peer-reviewed article
(Picone et al. 2023)	Peer-reviewed article
(Ji et al. 2023)	Peer-reviewed article
(Marin-Enriquez et al. 2022)	Governmental report

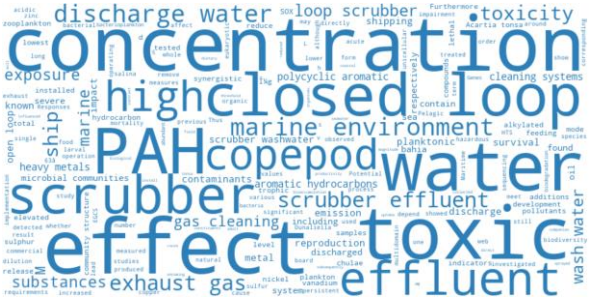

Figure 1. Word cloud of abstracts and titles of the key references listed in Table 2.

SCREENING STRATEGY

The screening will be conducted in two steps, an initial title and abstract screening and a full-text screening. The inclusion criteria for the two steps have been defined based on the PECO statement and language restrictions and are presented in Figure 2. The search will be restricted to only include studies in English, which is represented in the first criteria, and the second criteria limits the search to only include experimental studies. The third criteria reflect the population, defined as any marine species, and the fourth the exposure, which is scrubber water from any type of scrubber (open-loop or closed-loop. These four questions were considered possible to answer from reading the title and abstract. For the full-text screening the initial four questions will be the same. The two additional questions reflect the required comparator (natural seawater) and the outcome. As the study objective is to review all experimental studies investigating effects of scrubber water exposure on marine organisms, the accepted outcome statement is broad, and any endpoint will be included for full-text read and data-extraction. There are no pre-defined reasons for exclusion during full-text screening, but a list of the articles excluded at full text, including reasons for exclusion, will be provided.

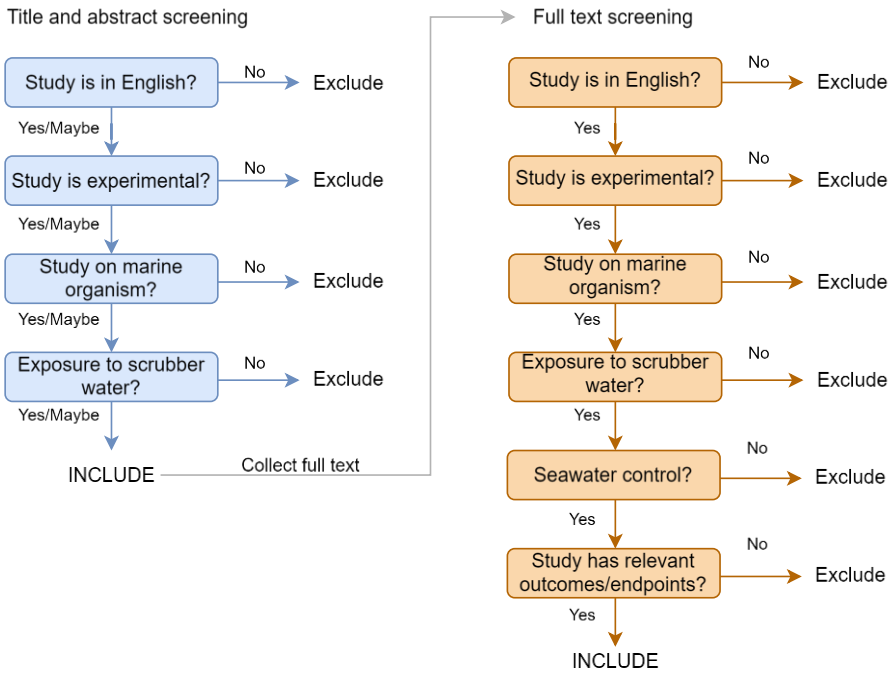

Figure 2. Decision tree for title and abstract screening (left) and full text screening (right).

After pooling of all search results, duplicates will be removed, using the Scopus results as the primary source. In cases where several studies are based on the same dataset (e.g. overlap between a conference proceeding, doctoral thesis, report, or peer-reviewed paper), only one version of the dataset will be included. The selection of study will be made on a case-by-case basis, including the study with the most comprehensive dataset and/or highest CRED-evaluation. A list of all studies excluded due to duplicate dataset will be provided, including reasons for exclusion. The final search and screening results will be presented according to the PRISMA flow-diagram template (Page et al. 2021).

The proportion of studies screened and checked for consistency by two or more reviewers will be approximately 10 % at each screening step (titles, abstracts, full-text). A single person will perform the screening of all the documents in the dataset (except studies they have co-authored) and the additional double-screening of a randomized 10 % of the dataset will be done by a group of the co-authors.

CRITICAL APPRAISAL STRATEGY

The reliability and relevance of the individual studies included after the full-text screening, will be assessed using the CRED framework (Moermond et al. 2016), using the online template developed by Science in Risk Assessment and Policy (SciRAP) (https://scirap.org) (Waspe et al. 2021). The data synthesis and PNEC derivation will only include studies CRED-evaluated as "Reliable without restrictions" or “Reliable with restrictions”. The results from the CRED-assessment will also provide a basis for discussing the variability in scrubber water constituents and investigated endpoints, and how they relate to the variability in risk assessments and statements regarding the adverse effects of scrubber water on the marine environment. Studies not fulfilling the CRED-requirements for inclusion in the data synthesis will still be included in the discussion of the narrative synthesis, as one of the review objectives is to map the reliability and relevance of the existing scrubber water literature.

Due to the limited time-frame of the study (< 6 months), a single person will perform the CRED analysis for all the studies included after the full-text screening (except in the case of their own work). To validate the assessment, the resulting CRED-reports will be discussed within the author group, mainly with regards to the more challenging assessments. Moreover, as part of the work within the EMERGE consortium, all ecotoxicological studies produced within the project include a CRED-analysis. Although these have been made by the authors of the studies, these previous assessments will be used as an indication of the repeatability and validation of the critical appraisal strategy. As all assessment protocols will be made accessible, future tests of repeatability and validation will be possible.

The body of evidence will be appraised using authors’ judgement, considering the diversity, consistency, risk of bias, strength of observed effects, reliability and relevance of the included studies, using a qualitative scoring system indicating the strength of the body of evidence (Table **3**) (US EPA 2016). The appraisal templet (Table **3**) is a modification and combination of the collective properties to consider when evaluating the body of evidence listed in US EPA (2016) and the considerations informing evidence synthesis judgement in US EPA (2022). The result of the body of evidence assessment will indicate the robustness of the derived PNEC value/s and potentially indicate which of the collective properties that needs to be addressed in future studies, to increase the strength and reliability of the body of evidence.

Table 3. Table of collective properties considered in the appraisal of the strength and reliability of the body of evidence. Each category is assessed by authors' judgement as either NE (No evidence), 0 (No effect, neutral or ambiguous), +/- (somewhat strengthens/weakens the body of evidence), ++/-- (strongly strengthens/weakens the body of evidence), or +++/--- (convincingly strengthens/weakens the body of evidence), including a motivation in support for the authors' judgement. Modified and combined from the approach presented in US EPA (2016) and US EPA (2022).

Category		Support for authors' judgement
Diversity	No. studies No. taxa No. life stages No. endpoints	Coherent result across a large diversity of relevant test-species, life stages and endpoints, can strengthen the body of evidence. A small diversity or lack of coherence between study results can weaken the body of evidence.
Consistency	Consistency Independence Coherence	Consistency and coherence in result over a larger number of reliable, relevant, and independent studies, can strengthen the body of evidence. Unexplained inconsistency or incoherence across reliable and relevant studies can weaken the body of evidence. If lack of study reliability or relevance can explain incoherent or inconsistent results, it does not have to weaken the body of evidence. If there are few studies included in the evidence base, consistency is difficult to assess, and the body of evidence is neither strengthened nor weakened.
Risk of bias	Absence of bias Sensitivity	A low risk of publication bias can strengthen the body of evidence and a high risk weakens it. Consistent result from a variety of different funders indicates a low risk of funding bias and can increase the weight of the evidence. A relevant set of tested species and endpoints can increase the weight of the evidence, but if many studies have tested species or endpoints with low sensitivity, it can weaken the body of evidence.
Strength	Dose-response Large/concerning magnitude/effect	A clear dose-response or a large/concerning magnitude or effect, can strengthen the body of evidence. A lack of an expected dose-response in reliable and relevant studies can weaken the body of evidence. If the data is insufficient to evaluate a dose-response curve, the body of evidence is neither strengthened nor weakened.
	Reliability	If a majority/all of the studies are assessed as "Reliable without restrictions" or "Reliable with restrictions" in the CRED-analysis, it can strengthen the body of evidence.
	Relevance	If a majority/all of the studies are assessed as "Relevant without restrictions" or "Relevant with restrictions" in the CRED-analysis, it can strengthen the body of evidence.

DATA EXTRACTION

The data and metadata extraction will be performed using the template in Appendix 1, and the extracted data will be quantitative parameters. The template has been designed to provide the information needed for the meta-analysis (results), the study characteristics needed for the reliability and relevance assessment (CRED-analysis), and the risk of bias assessment (see the templet info tab). In the derivation of the PNEC value the most sensitive end-point for each species will be used (Wheeler et al. 2002), but data will be extracted for every tested endpoint for each test species (see Appendix 1 for details). None of the metadata variables will be coded. The template has not been piloted, but many of the variables are directly linked to the questions in the well-established CRED-form (Moermond et al. 2016).

If any of the variables marked as "Required" or required "If applicable" in the template are missing, the study authors will be contacted via email (if possible) and asked to provide the missing data. Due to the short time-frame for the review, contacted authors will be given 2 weeks to reply, else the data will be marked as missing in the protocol.

One person will perform the data extraction from all studies, except their own. Consistency checking will be performed by having additional persons extract the data from approximately 10 % of the dataset (randomized), and then compare the agreement of the extractions.

POTENTIAL EFFECT MODIFIERS OR REASONS FOR HETEROGENEITY

The main source of heterogeneity in the dataset will be the anticipated large variation in scrubber water constituents and concentration. The scrubber water constituents and their concentration will depend on the fuel type, engine type, the operational mode of the ship (or experimental scrubber), the internal piping of the vessel, the seawater used, and the level of dilution (Lunde Hermansson et al. 2021). Consequently, every scrubber water is unique and variation in constituents, and thereby toxicity, is to be expected. This variability is inherent to scrubber water and as the objective of this review is to derive a PNEC value that reflects the large variability in scrubber water content and toxicity, the variability will not be corrected or normalized for. However, the heterogeneity will be thoroughly discussed with regards to the applicability of the synthesized review results when conducting e.g. risk assessments.

The composition of the natural seawater used as a comparator will differ between locations, hence is also a potential effect modifier. This effect will not be directly addressed but part of the potential effect will be considered indirectly via the assessment of relevance of the selected test-species. The remaining effect of the seawater is considered to capture the variation of conditions where scrubber water will be discharged, hence will not be corrected for, but will be reflected in the uncertainty and variation in the derived PNEC value.

The duration of the scrubber water exposure is another parameter that could modify the effect in the experiments compared to the environmental exposure of scrubber water. The experimental values are usually based on the assumption that the environmental exposure is constant, e.g. constant concentration of scrubber water in the water column where scrubber water has been released. Else, this potential effect modifier will be considered when assessing the relevance of the body of evidence, but no estimate of the actual contribution will be made.

An effect modifier relevant to consider when it comes to ecotoxicological studies with scrubber water, is the common practice/standard to filter the water or adjust the pH in the tested mixture (Magnusson and Granberg 2022). However, in the case of scrubber water, particles and low pH are important contributors to the toxicity (Koski et al. 2017) and should not be adjusted as it will decrease the relevance of the test (Magnusson and Granberg 2022). Tests using pH adjustment will therefore be considered less relevant compared to studies without pH adjustment.

The potential effect modifiers or reasons for heterogeneity in the dataset was discussed within the ecotoxicological group within the EMERGE project, representing five ecotoxicological laboratories across Europe.

DATA SYNTHESIS AND PRESENTATION

Data synthesis strategies

The data synthesis of the systematic review will be both narrative and quantitative. The narrative synthesis will include tables and figures illustrating the number and variety of taxonomic groups, test species, and scrubber water types in the reviewed studies. The CRED analysis results will be presented as a pie-chart with the number of studies in each evaluation category.

The quantitative synthesis will include data extracted from the studies evaluated as reliable in the CRED-analysis and will be a meta-analysis where the most sensitive endpoint from each test-specie will be used to derive a PNEC value. Using the most sensitive endpoint is a common approach when deriving species sensitivity distribution (SSD) curves, and it has been shown to be a conservative approach protecting sensitive species (Wheeler et al. 2002). If the extracted dataset includes studies of test species from > 8 taxonomic groups (as defined by TGD 27), a SSD

curve will be calculated, from which a probabilistic PNEC value can be derived (European Commission 2018). If the dataset includes test species from < 8 taxonomic groups, the PNEC value will be derived using the deterministic approach described in TGD 27 (European Commission 2018). If there are enough studies to fulfil the statistical requirements, a PNEC value will be derived for each scrubber type (open-loop, closed-loop, hybrid, and experimental). To be included in the derivation of the SSD curves, a study must provide an EC10-value (effective concentration that causes a 10 % effect) or a no effect concentration (NOEC) value for the tested endpoint, or present data from which either of these values can be derived (European Commission 2018). When using the deterministic approach, studies without NOEC values can still be used to inform the assessment factor.

The variability in the dataset will be accounted for by an AF, which will be chosen according to the procedure described in TGD 27 (European Commission 2018). With the deterministic approach the derived lowest available effect concentration (critical value) is divided by the AF to yield the PNEC (European Commission 2018). For the probabilistic approach, the derived SSD curve will be used to determine the median estimate of the HC5 value (concentration at which 5 % of all species are affected), which is divided by the AF to give the PNEC (European Commission 2018).

As a sensitivity analysis, both the deterministic and probabilistic approach will be used to derive a PNEC value, to investigate if/how the methodological approach affects the PNEC value. This will be done irrespective of the number of taxonomic groups in the included dataset.

Assessment of risk of publication bias

The dataset publication bias will be assessed visually using a funnel plot (a scatterplot of study effect size on x-axis against standard error on y-axis) and statistically using Egger's Regression intercept and the skewness of the standardized deviates (Lin and Chu 2018), to quantify the funnel plot asymmetry. Another important bias to consider in ecotoxicological studies is funding bias (Hoffmann et al. 2017), which it is particularly relevant in the scrubber water case. To evaluate and assess the funding bias, information about the study funder and any statements/recommendations based on the study results regarding the risk of scrubber water discharge, is included as a required meta-data variable in the data-extraction template (Appendix 1). The funding bias will be visually assessed from a scatter plot with the study conclusions regarding the risk of discharging scrubber water versus the type of funder.

Ensuring procedural independence

All studies will be reviewed by an independent reviewer. The person who will conduct the majority of the systematic reviews (A. T. Nylund) has only been part of a few scrubber-related publications, and not been involved in any of the experimental studies conducted within the EMERGE project. Studies where A. T. Nylund is a co-author will be screened and considered by another, independent author. Authors that will be reviewed have been part of deriving the inclusion criteria, decision trees, and templates for the screening and data extraction, but no author will review their own work.

DECLARATIONS

The authors declare no competing interests.

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