

POLICY BRIEF

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Regulation of chemical emissions from offshore wind farms: comparative analysis and policy recommendations for the North Sea

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Abstract

The offshore wind energy sector is experiencing rapid and large-scale expansion in Europe, driven by increasingly ambitious renewable energy targets that position it as a central component of global climate mitigation efforts. The increasing number of offshore wind projects in the North Sea requires comprehensive regulations to monitor and minimize the impacts on the marine environment during construction, operation and decommissioning. This policy brief aims to summarize current regulations for chemical emissions in the North Sea area by reviewing available national documents and websites for guidance in Belgium, Denmark, France, Germany, the Netherlands, and Norway in combination with information received from respective authorities. Based on the collected information, the policy brief will give recommendations for potential harmonization to increase the protection of the environment and facilitate procedures. The comparative analysis of national and transnational regulations for chemical emissions from offshore wind farms in North Sea bordering countries revealed that these are incomplete and differ between countries in terms of their specifications and level of detail. For example, specific rules for the application of galvanic anodes including the ban of zinc-based anodes are only available in Germany while several but not all countries prohibit the use of antifouling or other toxic paints. Incompleteness and differences may also be related to a lack of information on substances and their environmental effects. To achieve harmonization and more efficient protection of the marine environment, more data and minimum requirements on a regional level will be necessary, while at the same time, innovation may not be hampered and design and techniques should be further optimized and adapted based on latest available information.

Keywords Chemical emissions, Regulations, Offshore wind farms, Environmental impact, North Sea

Offshore wind energy: chances and challenges

Climate change has led policymakers in several countries to make decisions favoring the energy transition away from fossil fuels towards renewable energies. Wind energy production, on land as well as offshore, has increased significantly over the past two decades. It has become one of the most important sectors in the energy transition, securing the energy supply while phasing out fossil fuels and thus contributing to mitigate climate change. Between 2019 and 2023, the global offshore wind energy capacity increased by 157% and an accelerated increase is expected during the next decades [23].

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The European Union (EU) pursues the expansion of renewable energies, including offshore wind energy, to accomplish the energy transition and become independent from energy suppliers and fossil fuel-delivering countries outside Europe [15, 20]. In 2024, the installed offshore wind capacity in the EU was already 21 gigawatt (GW), with Denmark having the highest share of offshore wind energy in their energy mix (26%) and Germany having the highest installed capacity (~9,100 GW) [42]. According to the Ostend Declaration of Energy Ministers in April 2023, the objective is to increase the capacity of offshore wind energy in North Seas to 120 GW and at least 300 GW installed by 2030 and 2050, respectively [33]. Accordingly, countries bordering the North Sea aim to revise their energy transition targets and expansion of offshore wind capacity.

The rapid extension of offshore wind farms (OWFs) requires a suite of key aspects to be evaluated and approved by each country's authorities prior to operation. This covers the planning, licensing and construction, but also operational and decommissioning processes. For these processes, also environmental aspects have been integrated into administrative and regulatory procedures. For example, specific areas have been designated for offshore wind energy expansion in national marine spatial and/or site development plans, and strategic environmental assessments have been carried out (e.g. [4, 6, 27, 39]).

Scientific research on chemicals introduced into the marine environment by OWFs has only recently begun and only few studies are available, especially focusing on metal release from galvanic anodes used for corrosion protection and laboratory studies on leachates from coatings (e.g. [3, 11, 12, 44]). Therefore, information on possible sources and types of chemicals applied at OWFs is scarce and was only recently reviewed [21]. Additionally, ecotoxicological data for the emitted chemicals are often missing. While some compounds are listed as chemicals of concern and are at least under observation, for numerous chemicals, risk assessments for the marine environment are lacking [21].

In the EU, the Marine Strategy Framework Directive (MSFD) and the Water Framework Directive (WFD) aim to achieve a good environmental and chemical status of the marine and coastal environments and address pollution by chemical contaminants in the seas in general, but not specifically for OWFs or other potential contaminant sources. According to the MSFD (Descriptor 8), concentrations of pollutants at sea are supposed to be at levels that do not result in any pollution effects [16]. Further, the EU zero-pollution action plan aims to increase environmental protection from hazardous chemicals and reduce, for instance, specifically microplastic pollution

by 30% by 2030 [14]. With respect to chemical emissions from OWFs, there is no directive in place at EU level. The Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) gives first recommendations with respect to environmental impacts of OWFs, like noise effects, input of waste and chemical pollutants and impacts on habitats and fauna [30]. However, at the moment, implementing regulations is the responsibility of each country.

Differences and gaps in regulations on chemical emissions from OWFs on a European or national level can lead to insufficient protection of the marine environment. Building upon the scientific review by Hengstmann et al. [21], that summarizes the state of research for chemical emissions from OWFs, this policy brief focuses on the regional structure of regulatory frameworks and provides policy-related recommendations. Therefore, this policy brief addresses regulations on chemical emissions from OWFs in North Sea bordering countries in the European Economic Area (EEA) with the objective to (i) give an overview of existing national regulatory approaches, (ii) identify differences between countries and overall gaps and (iii) recommend next steps for the further development of regulations on chemical emissions from OWFs. Thereby, the policy brief aims to increase the protection of the environment and facilitate licensing procedures.

Methods

Existing regulations for chemical emissions from OWFs were compared for a selection of EEA states bordering the North Sea, namely Belgium, Denmark, France, Germany, the Netherlands, and Norway. An overview of OWFs in the respective countries is, for example, provided by OSPAR Data & Information Management System [32]. An online research combining topic-related English keywords (see Supplementary Information (SI) Part A) identified publicly available documents and national websites which provide information on regulations in place. Primary and grey literature in English and national languages was considered, including scientific studies, reports, primary legislative documents and implementing decrees as well as guidance documents. In parallel, regulating authorities for OWFs in the respective countries were contacted to identify not publicly available information and to validate interpretations from the online research. In total, 70 sources of information were reviewed for specific regulations on chemical emissions from OWFs. Of these, 51 were considered in further analysis. The research was mainly carried out in the first half of 2024. We therefore present the status of regulations as of June 2024.

The selection of countries is based on the partnering countries in the EU Interreg project Anemoui. Even

though the United Kingdom (UK) currently has the highest cumulative capacity of offshore wind energy in Europe, it was not considered in this study. Regulatory approaches in the UK have been compared with those in the United States (US) and Germany in a review by Hengstmann et al. [21]. English was the primary language for the online research but information in national languages was still retrieved. Such documents were translated which may lead to loss of information or translation errors. Furthermore, all documents and websites identified in the online research were publicly available, excluding information with restricted access. Therefore, public authorities were contacted and asked for further information and documents. Still, it cannot be ruled out that restricted, internal guidelines were omitted.

Relevant information on regulations in the different countries was gathered, the overview table is provided in the SI Part B. Based on the compiled results, regulatory frameworks were compared between the countries and gaps across countries were identified. Furthermore, recommendations for more in-depth regulations as well as possible harmonization approaches were developed. A draft version of the policy brief was presented to stakeholders of the EU Interreg project Anemoi. The feedback received has been incorporated.

For more information on the procedure, please see the SI (Part A).

Comparison of existing regulations in countries bordering the North Sea

Comparing the above-mentioned countries with respect to regulations on chemical emissions from OWFs, several differences but also similarities become visible (Table. 1 and SI Part B). In general, the protection of the environment is of importance in every country and reduction of the impact on the environment by anthropogenic activities is an overall goal. This is in line with international (e.g. United Nations Convention on the Law of the Sea) and regional (e.g. Oslo Paris Convention) agreements, which call for the prevention, reduction and control of possible pollution of the marine environment [31, 37]. Furthermore, the *OSPAR Guidance on Environmental Considerations for Offshore Wind Farm Development* provides recommendations for chemical emissions from OWFs which affect all countries considered in the analysis, as the North Sea is part of the OSPAR region. These guidelines state that the threat of marine pollution by hazardous substances (from construction or operation) needs to be minimized, the risk of chemical pollution incidents should be reduced and scouring material should be free of chemical contaminants [30]. Regardless of the extent to which the OSPAR regulations have been implemented in the North Sea coastal states, it is permissible to go beyond the OSPAR regulations. In some cases, this option is also being exercised. Furthermore, the provisions of the European Renewable Energy Directives, most recently Directive (EU) 2023/2412 (RED III), have an impact on national requirements for OWFs as these must be transposed into national law. This directive

Table 1 Selection of existing regulations on chemical emissions from OWFs in considered countries

Country	General	Impact assessment	Monitoring available for			Anodes	Coatings
			Biology	Water/hydrodyn	Chemicals		
Belgium	<i>Introduction of substances not allowed</i>	<i>Rules available</i>	Yes	Yes			<i>Toxic paints not allowed</i>
Denmark	<i>Reduce negative env. impacts</i>	<i>Rules available</i>	Yes				
Germany	<i>Minimise chemical emissions; Reduce negative env. impacts</i>	<i>Rules available</i>	Yes			<i>ICCP (preferred); Galvanic + coatings; Zn anodes not allowed; Reduce impurities</i>	<i>Antifouling paints not allowed</i>
France	<i>Reduce negative env. impacts</i>	<i>Rules available</i>	Yes	Yes		<i>Project dependant; Galvanic & ICCP allowed</i>	<i>Antifouling paints not allowed</i>
The Netherlands	<i>Introduction of substances not allowed</i>	<i>Rules available</i>	Yes				<i>Specific types allowed</i>
Norway	<i>Reduce negative env. impacts</i>	<i>Rules available</i>	<i>Generally required, no information on focus</i>				

For a more comprehensive overview see SI (Part B). *hydrodyn* hydrodynamics, *env* environmental

determines specifications for carrying out environmental impact assessments.

Considering country-specific regulations, impacts from OWFs on the marine environment with respect to biodiversity or specific organisms are often mentioned (e.g. [8, 9, 34, 36]). In contrast, specific sources for chemicals introduced into the marine environment are less frequently addressed in regulating documents. Also, these rules differ among countries with respect to detail, scope and extent. The variation in regulatory approaches, concerning authorisation processes and especially rules for chemical emissions from OWFs, was also shown by other authors (e.g. [21, 38]). Hengstmann et al. [21] further compared the legal frameworks for Germany, the UK and the US. Their results showed that neither the UK nor the US have specific regulations for chemical emissions from OWFs, but individual licence conditions and other legal frameworks will regulate chemicals used in OWFs on a broader scale. In the following, the regulations on monitoring approaches and specific chemical emission sources are compared for Belgium, Denmark, France, Germany, the Netherlands, and Norway. Special attention is given to two regulatory aspects in the spotlight chapters, to underline the differences in approaches across countries.

In general, monitoring approaches are implemented and/or required for OWFs in several countries, but the focus and the responsible authority differ. Monitoring focusing on water quality and biological aspects (benthic communities, fishery resources, marine mammals, chiropteran activity) is required to be undertaken by the project owner during the lifetime of the project in France [1, 26, 28]. In contrast, a monitoring of metals in water, sediment and benthos is recommended but not required in France [1, 28]. Similarly, monitoring programs in other countries are rather concerned with biological aspects but do not consider chemical emissions. For example, in Germany, assessments of impacts on benthos, birds and marine mammals must be carried out by the operator during the construction and the first ten years of operation of OWFs [5, 43]. In the Netherlands and in Belgium, monitoring is required by law and research and monitoring programs to assess ecological and biological effects of OWFs (WOZEP and WinMon.BE, respectively) have been established by national authorities [10, 35]. Likewise, an environmental monitoring program has been implemented in Denmark to analyze long-term and cumulative effects on specific species [7].

Corrosion protection systems are considered one of the major input pathways for chemical emissions from OWFs [21]. Therefore, it is important to have regulations on their application. However, such regulations are only rarely defined in the evaluated countries and often lack specific, enforceable requirements at this point.

For example, regarding the use of coatings for corrosion protection of offshore wind structures, the Dutch regulations recommend that epoxy coatings with little to no release of specific compounds should preferably be applied [22]. Similarly, Belgium, French and German rules require coating material which is as pollution-free as possible and/or forbid coatings and paints that include tributyltin and other biocides (e.g. [4, 19, 28]). The ban of tributyltin, an organotin compound which was frequently used in antifouling paints for ships, was implemented in 2008 by the International Convention on the Control of Harmful Antifouling Systems by the International Maritime Organization (IMO) [40].

Besides coatings, anodes are applied at OWFs to prevent corrosion of steel structures [24], especially for submerged areas [41]. Galvanic anode cathodic protection (GACP) systems based on zinc as major compound are prohibited in Germany to reduce the input of respective metallic components into the marine environment. Instead, aluminum-based galvanic anodes, minimizing the zinc content as well as other impurities, are allowed and, if possible, impressed current cathodic protection (ICCP) systems are preferred due to their very low metal emissions [4]. As the release of metallic compounds from galvanic anodes was observed, monitoring of any metallic contamination from OWFs and considerations to apply ICCP systems to minimize any emission of metals is recommended in France [1, 28]. In other countries in this study, specific rules for the application of anodes have not yet been introduced.

Spotlight 1: source-based approach

In Germany, a source-based approach considers different input pathways for chemical emissions from OWFs and defines specific rules for their avoidance or minimisation [4]. This includes for example scour protection measures, wastewater and drainage systems or cooling circuits. At the same time, operators are required to submit an emission concept during the approval stage of OWFs in Germany, which summarizes possible emissions from different sources and avoidance strategies. During project development, this concept needs to be updated in the form of an emission study, containing the actual emissions. Additionally, a list of all operating materials on the wind turbines and platforms must be submitted [4]. Such a source-based approach addressing various possible sources for chemical emissions is not yet established in regulatory frameworks of other countries considered in this analysis. A similar approach with respect to the listing of materials, is available in Belgium, though. Here, a list of all hazardous and noxious chemicals planned to be used shall be submitted for approval to the supervisory committee (e.g. [19]).

Spotlight 2: microplastics

When looking at microplastics, which may be emitted in the form of coating particles and/or particles from rotor blade erosion, two different regulatory approaches have been implemented in the countries considered. In Belgium and in the Netherlands, microplastics or specific polymers are explicitly regulated. In Belgium, measures to limit the emission of microplastics are required to be described and submitted for approval to the committee supervising the ongoing activities at sea [18]. In the Netherlands, rules for epoxy coatings are in place [22]. In contrast, microplastics and polymers are not explicitly addressed in other national regulations but are implicitly covered by general minimization rules. Here, emissions are supposed to be minimized and/or introduction of substances is prohibited (e.g. [2, 4]) which may also include particulate matter from coatings or rotor blades.

Recommendations and need for action

To summarize, the presented overview of national regulatory approaches in several North Sea bordering countries shows that first regulations concerning chemical emissions and their monitoring have been implemented, for example for corrosion protection measures. The comparative analysis also reveals a substantial discrepancy across countries regarding the specification of guidelines: rules vary in the level of detail and not all types and sources of emission are addressed. Transnational recommendations, e.g. by OSPAR, address chemical emissions vaguely. However, detailed recommendations could be effective in reducing chemical emissions e.g. as shown by the OSPAR recommendations for offshore oil and gas installations [29]. Therefore, we see a clear need to address and tackle the aspects named and described in the following subchapters in future (also see Fig. 1).

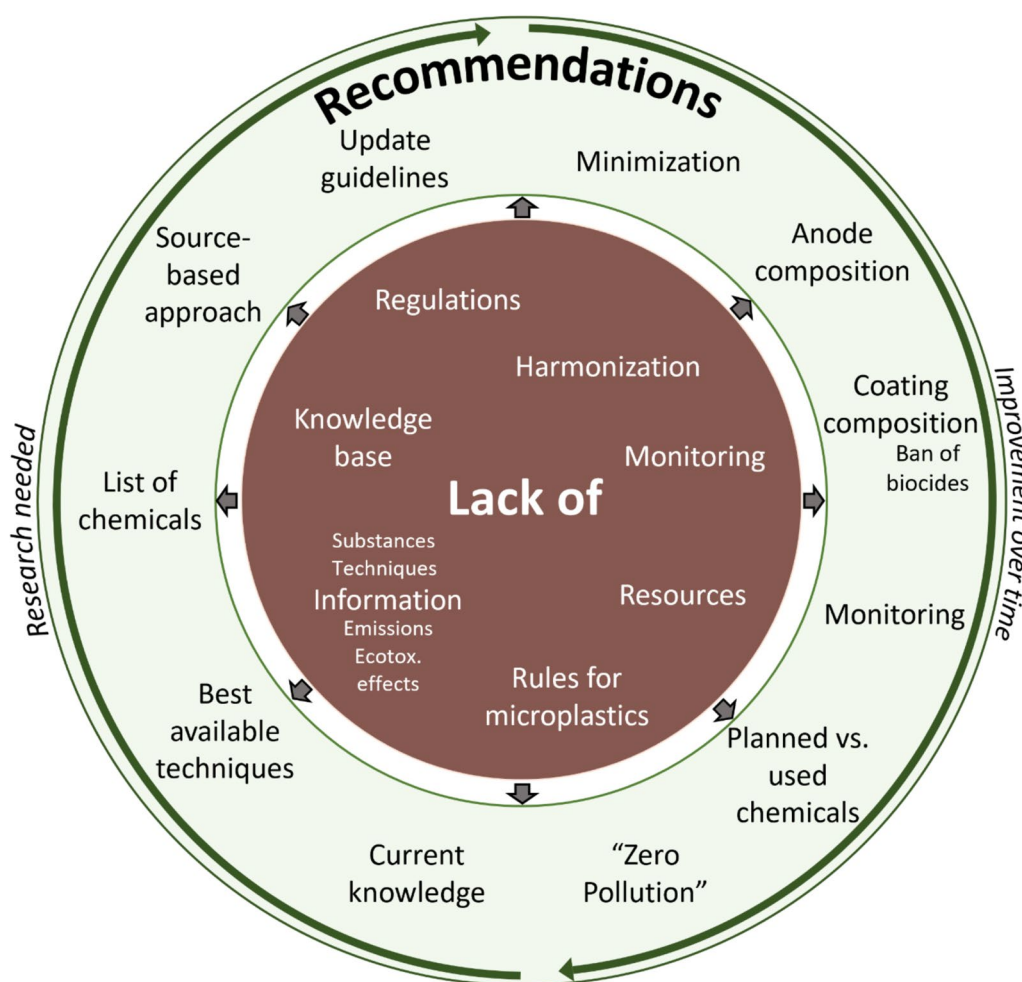


Fig. 1 Overview of identified lacks with respect to regulations on chemical emissions from OWFs and possible steps for improving regulations in future

Minimum requirements

The general goal of minimizing emissions from OWFs is already part of country-specific and transnational regulations, but should be further specified for chemical emissions. In a first step, minimum requirements may focus on selected topics e.g., corrosion protection measures or regulatory approaches. As a basis, regulations concerning chemical emissions that are already in place, like the ban of biocides in coatings (several countries) and rules for minimizing microplastic emissions (Belgium and Netherlands), may be adapted in other North Sea bordering countries. A source-based approach for regulating chemical emissions in combination with detailed emission studies on actual emissions in offshore projects (Germany) may help to extend rules specifically for chemical emissions from OWFs. The preference for ICCP instead of GACP (as expressed by Germany and France) may be one solution to reduce the emission of metals but may introduce halogenated compounds [25]. However, information on potential emissions from ICCP and their impacts on the marine environment is scarce. Future studies need to provide more and transparent data in order to better assess the impact of alternative technologies such as (but not restricted to) ICCP in a possible process of harmonization of regulations.

Consequently, a next step is to phrase minimum requirements for regulating emissions of chemicals from OWFs depending on the applied techniques (source-based approach).

Monitoring and data needs

Having a comprehensive overview of applied chemicals on OWFs and their ingredients can be beneficial for the estimation of chemical emissions and their impacts. As shown in a review by Hengstmann et al. [21], there is a lack of scientific data on the composition of chemicals used in specific offshore wind applications (e.g. coatings) as well as chemical emissions and their ecotoxicological assessment. Further research and international databases on chemical contaminants from OWFs are needed. When national authorities require lists of planned and used chemicals in OWFs in the authorization process (building on the procedures already in place in Germany and Belgium), this information may help in identifying chemicals that may be of concern. Furthermore, chemicals that lack data for risk assessment for the marine environment should be evaluated before they are utilized in OWFs. The more information on chemicals and their emissions and impacts will become available, the better they can be evaluated.

Moreover, data on emissions and their impacts on the marine environment should be gathered in general. Monitoring during the operational phase is an important tool

to do so and could be inspired by established monitoring procedures used in other sectors, like offshore oil and gas. Results from monitoring can help determine emissions more precisely, identify those contaminants that show large releases, enrichment in water, sediment or biota and/or are of concern due to potential impacts on the environment. Overall, increasing the knowledge on chemical emissions from OWFs through monitoring and research, as well as sharing data on chemical substances used and monitoring results publicly, may contribute to the goal of reducing emissions of prioritized chemicals.

On that account, there is a need to monitor and study chemicals from OWFs scientifically to extend knowledge on the emissions and better assess their occurrence and effects in the marine environment.

Balance between regulation and innovation

With additional data gained by an overview of applied chemicals in OWFs and monitoring programs, new innovative technologies may be developed, designs already in use can be optimized and Best Available Techniques (BATs) may be revised and improved to limit chemical emissions. It is important to review regulations and BATs regularly to ensure that they reflect the latest findings and adapt them, if necessary. Adapted and optimized regulations and techniques could then address specific emissions in order to minimize pollution. When implementing harmonized regulations, it should be considered though, that these do not impede innovation of different techniques but still allow for their development. The difficulty of reconciling regulation and innovation is a cross-sectoral issue. So-called “experimentation spaces” can ensure greater flexibility in a protected regulative environment [13] and could also be applied in the offshore wind sector. At the same time, fragmentation in regulations between countries is also known to hinder innovation [17] so that harmonization may also be beneficial in this respect.

Therefore, adaptation and expansion of guidelines, regulations and BATs with increasing knowledge on chemical emissions from OWFs must go hand in hand with sufficient scope for innovation and feasibility.

Coordination efforts

Further development of regulations addressing chemical emissions from OWFs should also take into consideration to harmonize rules transnationally aiming towards the minimization of impacts on the environment already in the design phase. A harmonization of regulations would also be beneficial for developers and operators that manage OWFs in various countries. However, it is important to clarify to what extent regulations can be established on an overarching level. Chemical emissions will spread

in the North Sea regardless of the point (country) of entry. Coordination across national borders, e.g. on sea basin level, could help protect the marine environment in a more integrated way. At the same time, a sea basin (or European) wide coordination regarding minimum requirements for chemical emissions from OWFs must consider a wide audience, involving stakeholders, policy makers, authorities, scientists and society. A strong involvement of the different stakeholders is necessary to implement the first steps with respect to more detailed and overarching regulations for chemical emissions from OWFs.

Thus, carefully coordinating rules for chemical emissions on a transnational level is essential for more effective protection of the marine environment and to provide clear guidelines for operators.

Final remarks

We seek our evaluation and recommendations for extending knowledge and for specifying, regularly reviewing and harmonizing regulation on chemical emissions from OWFs, will contribute to improved protection of the marine environment. A minimization of emissions from OWFs will also serve the goals of transnational frameworks like the WFD or MSFD which aim to achieve a good environmental status of the marine environment. According to the Pollution Action plan of the EU, the final policy goal would be a “zero-pollution” scenario, which does not literally imply a zero emission of chemicals but their reduction to such an extent that there are no effects on the marine environment. Furthermore, the EU blue growth strategy was introduced in 2021 to ensure the parallel development of marine economy sectors as well as marine conservation. Therefore, the recommendations made in this policy brief are in line with European initiatives and underline the necessity of transnational cooperation, which has become even more important in the last decades, to increase the protection of our oceans while supporting the sustainable development of offshore energy supply.

Abbreviations

BAT	Best Available Techniques
EEA	European Economic Area
EU	European Union
GACP	Galvanic anode cathodic protection
GW	Gigawatt
ICCP	Impressed current cathodic protection
IMO	International Maritime Organization
MSFD	Marine Strategy Framework Directive
OSPAR	Convention for the Protection of the Marine Environment of the North-East Atlantic
OWFs	Offshore wind farms
SI	Supplementary Information
UK	United Kingdom
US	United States
WFD	Water Framework Directive

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s12302-026-01329-4>.

Supplementary material 1.

Supplementary material 2

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Author contributions

EH conceptualized the study, conducted the literature and online research, processed and analysed data, drafted the manuscript, substantively revised it and generated visualisations. MH conducted the literature and online research, processed and analysed data and drafted the manuscript. AP was involved in literature research, processed and analysed data and substantively revised the manuscript. BDW acquired funding, conceptualized and supervised the study, analysed data and substantively revised the manuscript. KDC was involved in literature research, analysed data and substantively revised the manuscript. TB analysed data and substantively revised the manuscript. DV analysed data and substantively revised the manuscript. DJD analysed data and revised the manuscript. IW was involved in literature research and substantively revised the manuscript. SH acquired funding, conceptualized the study and substantively revised the manuscript. All authors read and approved the final manuscript.

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Data availability

Datasets generated during this study and supporting the conclusions are included in this published article and its additional files.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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