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Guidance on integrating marine environmental impacts of ocean alkalinity enhancement into life cycle assessment

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Abstract

Purpose Ocean alkalinity enhancement (OAE) is considered a promising marine carbon dioxide removal (mCDR) option and may contribute to climate change mitigation. Life cycle assessment (LCA) is used to assess OAE environmentally but faces limitations in capturing marine impacts. Improving the assessment of OAE in LCA requires a detailed understanding of its marine environment impact pathways to develop sub-compartmentalised and regionalised characterisation factors (CFs). We demonstrate how such pathways can be identified.

Methods We build on Woods et al. (2021), who propose a qualitative framework to identify key components of impact pathways, and Richter et al. (2024), who provide guidance on framework development in a multidisciplinary context. We develop a methodological approach that allows to qualitatively identify the marine environmental impact pathways of OAE and determine which components are integrated in LCIA models or missing, as an initial phase toward developing CFs for life cycle impact assessment (LCIA).

Results and discussion Our methodological approach includes: (1) the selection of literature on OAE and its impacts on marine ecosystems; (2) the identification of the marine elementary flows in the life cycle inventory and the fate, exposure, and effect processes; (3) the inputs from LCIA, oceanography, and technology experts; (4) the review of LCIA models to examine which elements of the marine environmental impact pathways are represented or lacking; (5) the definition of research priorities to advance the assessment of OAE's environmental impacts within LCA. We identified three impact categories associated with OAE marine environmental impacts pathways: marine ecotoxicity, marine eutrophication, and ocean acidification. Existing LCIA models only partially capture these pathways and require adaptation for assessing comprehensively OAE. Research priorities include conducting additional experiments on the ecotoxicological and eutrophic effects of OAE deployment in marine environments, and the effect of added alkalinity on a broader range of marine calcifiers. Several of our recommendations are also relevant to enhance marine technologies' assessments in LCA more broadly, such as improving the ocean's representation in models, modelling direct release to offshore marine waters, and broadening the elementary flows' coverage for marine eutrophication.

Conclusion We present a methodology to identify marine environmental impact pathways of OAE, providing a first phase toward developing CFs. The methodological approach might be adapted to other marine technologies, where identifying impact pathways require a multidisciplinary approach that combines the LCA field with oceanography and engineering expertise.

Keywords LCA · LCIA · Impact assessment · Impact pathway modelling · OAE · Marine carbon dioxide removal · MCDR

1 Introduction

Meeting climate targets to limit global warming to well below 2°C requires substantial reductions in greenhouse gas emissions (IPCC 2023). Interest in atmospheric carbon dioxide removal (CDR) approaches has grown substantially due to their potential to complement deep emissions cuts to achieve these targets. Ocean alkalinity enhancement (OAE) is regarded as one of the most promising marine CDR (mCDR) options (Smith et al. 2024; De Pryck and Boettcher 2024; Oschlies et al. 2025), with the first OAE carbon credits recently issued (Isometric 2025). This emerging mCDR approach aims to enhance carbon dioxide (CO₂) uptake from the atmosphere by the ocean through intentional addition of alkaline materials to seawater (Renforth and Henderson 2017; Oschlies et al. 2025). While currently being tested at the field level, OAE could enable the removal of billions of tonnes of CO₂ annually at scale (He and Tyka 2023; Ringham et al. 2024).

Life cycle assessment (LCA) is used to evaluate the net carbon removal capacity of OAE and potential environmental trade-offs it may entail (Foteinis et al. 2022, 2023; Yang and Feng 2026; Katish et al. 2026; Myridinas et al. 2026). However, critical limitations remain in the LCA methodology to comprehensively assess impacts of OAE on marine environments (Foteinis et al. 2022; Delval et al. 2025; Katish et al. 2026; Myridinas et al. 2026). Life cycle impact assessment (LCIA) method families (e.g., CML, ReCiPe, or TRACI) traditionally focused on impacts on terrestrial and freshwater ecosystems, and while they have begun to address impacts on marine ecosystems over the last decades (Huijbregts et al. 2000; Dong et al. 2016; Verones et al. 2020), these impacts remain underrepresented. Currently, the most common LCIA method families include up to three impact categories assessing marine environmental impacts: marine eutrophication, marine ecotoxicity, and marine acidification, all of which leading to ecosystem damage. These categories could be insufficient to capture the full range of OAE's marine environmental stressors or could fail to adequately account for some important considerations of marine environmental impacts caused by OAE. For instance, only nitrogen (N) flows are characterised in the marine eutrophication impact category, whereas other nutrients released by some OAE approaches could contribute to marine eutrophication, such as iron (Fe) (Bach et al. 2019; Guo et al. 2024).

A further limitation in LCIA models is their spatial resolution of the ocean. These models simplify the ocean by only considering coastal seas (Struijs et al. 2009) or by only distinguishing coastal seawater and three climate zones (Huijbregts et al. 2000; Van Zelm et al. 2009), which substantially neglects its spatial heterogeneity and depth

dimension. While more recent models better account for this heterogeneity by distinguishing dozens of different large marine ecosystems (LMEs) (Dong et al. 2016, 2018; Cosme et al. 2018), these LMEs are constrained to continental shelves (Sherman and Donnelly 2026), thus remaining unsuitable for assessing the impacts of OAE when deployed in the open ocean.

To enable more comprehensive evaluations of OAE's environmental performance in LCA and determine the suitability of this mCDR approach within the CDR portfolio for climate change mitigation, it is essential to understand the impact pathways through which this technology affects marine environments. Additionally, the spatial context in which these processes occur must be considered regionally and by dividing the marine compartment into relevant sub-compartments that reflect the ocean's spatial variability, as proposed in similar work for marine microplastic impacts (Hajjar et al. 2024). Ultimately, integrating these pathways may require the development of new or improved marine impact category indicators that incorporate characterisation factors (CFs) specific to the relevant marine regions and sub-compartments (Delval et al. 2025).

In this work, we aim to develop a methodological approach that allows for: (i) identifying marine environmental impact pathways of OAE, (ii) understanding which components of these pathways are already covered in current LCIA models, and (iii) determining the research needs to integrate these pathways in LCIA comprehensively. Identifying these pathways represents the basis for developing sub-compartmentalised and regionalised CFs. Overall, the findings of this work could strengthen the representation of marine environmental impacts within LCIA beyond OAE, and the developed approach could be applied in future research to other technologies deployed in and interacting with the ocean.

2 Method

In the LCIA phase, elementary flows (i.e., matter or energy inputs extracted from the environment without previous human processing or outputs released into the environment without subsequent human processing) identified in the life cycle inventory (LCI) phase are translated into environmental impact scores using CFs. These CFs are derived from characterisation models, which are mathematical representations of impact pathways (also called cause-effect chains). Impact pathways describe the mechanisms connecting elementary flows to damages affecting areas of protection (AoP). These AoP in LCA are the natural environment, human health, and resources and ecosystem services (Hauschild and Huijbregts 2015). Impact pathways often consist

of three types of processes: 1) fate processes, which describe the spatial distribution, residence time, and chemical behaviour of a substance released into the environment; 2) exposure processes, which describe how sensitive receptors (e.g., receptors likely to suffer negative effects, such as marine species and ecosystems) get exposed to the substance; and 3) effect processes, which assess the effects to AoP resulting from this exposure (Woods et al. 2021).

Here, we aim to develop a methodological approach that allows to qualitatively identify these processes for OAE's marine environmental impacts and inform on knowledge gaps and research priorities for their integration in LCIA models. The starting point to improve assessment of marine environmental impacts in LCIA is often a marine impact category not yet covered by existing LCIA method families, such as ocean acidification (Anderson et al. 2025) or marine litter (Hajjar et al. 2025). While these efforts are essential for advancing LCA, we, however, opt for an approach that starts at the technology level and its elementary flows to ensure that all potential marine environmental impacts associated with that technology are comprehensively identified and integrated into LCIA models. Such an approach would complement existing efforts in LCIA modelling to allow a comprehensive assessment of marine environmental impacts of technologies in LCA.

Our approach builds on Woods et al. (2021), who conducted a similar study on impact pathways for marine plastic litter. They propose a framework that qualitatively identifies the key components of marine litter's impact pathways, which is an important first step in coordinating future efforts in LCIA development. Their approach also highlights the importance of spatial differentiation and identification of elementary flows. However, the methodology used to construct their framework is not described in detail, limiting its replicability for other technologies or impact categories. Clear methodological guidance is particularly important for impact pathway identification, which typically requires involving experts from multiple backgrounds, such as LCA practitioners, industrial experts, and environmental biologists. For framework development in a multidisciplinary context, the systematic methodology from Richter et al. (2024) provides valuable guidance. The authors followed a five-step methodological approach to identify the key aspects required for assessing animal welfare impacts of food products in LCA, combining insights from relevant literature with input from multidisciplinary experts. Their approach transparently documents the means used and the outcomes obtained at each step, thereby enhancing the clarity and the reproducibility of the methodology.

Rather than proposing a fundamentally new LCIA development methodology, our contribution lies in adapting and operationalising existing pathway-development concepts

for the specific challenge of OAE-related marine interventions. Therefore, we developed a methodological approach that combines elements from Woods et al. (2021) and Richter et al. (2024). Similar to the framework proposed by Woods et al. (2021), our approach enables the identification of the key components of impact pathways as well as knowledge gaps for their integration in LCIA. Moreover, following Richter et al. (2024), we structured our methodology as a transparent step-by-step approach with clearly defined inputs and outputs at each stage.

3 Results

3.1 Methodological approach for the identification and integration of OAE's marine environmental impacts in LCA

We developed a methodological approach to qualitatively identify the key processes for OAE's marine environmental impact pathways and to determine the current knowledge gaps and research priorities for integrating these pathways in LCIA models. This is an initial phase laying the groundwork for future efforts to build fate, exposure, and effect models from which corresponding fate, exposure, and effect factors and ultimately CFs can be derived.

Our methodology (Fig. 1) consists of five steps: (1) selecting relevant oceanography and geochemistry literature on OAE and its impacts on marine ecosystems; (2) identifying the main components of OAE's marine environmental impact pathways (e.g., the relevant marine elementary flows in the LCI, as well as their associated fate, exposure, and effect processes); (3) revising the identified marine environmental impact pathways through review by experts, with expertise in either LCIA, oceanography, or OAE; (4) reviewing the LCIA modelling literature to assess which aspects of the identified marine environmental impact pathways are represented in existing LCIA models and which remain absent; (5) defining research priorities to enhance the assessment of OAE within LCIA.

We followed the five steps of the developed methodological approach. A detailed technical description of OAE is given in the supplementary information (SI, Section A). Given our focus on marine environmental impacts, we limited our analysis to impact pathways for substances released into the marine environment by OAE (Fig. 2), and we focused on marine species and ecosystems as the sensitive receptor. Details on impact pathways for humans and structures with instrumental or cultural value to humans, considered sensitive receptors, are provided in the SI (Section B).

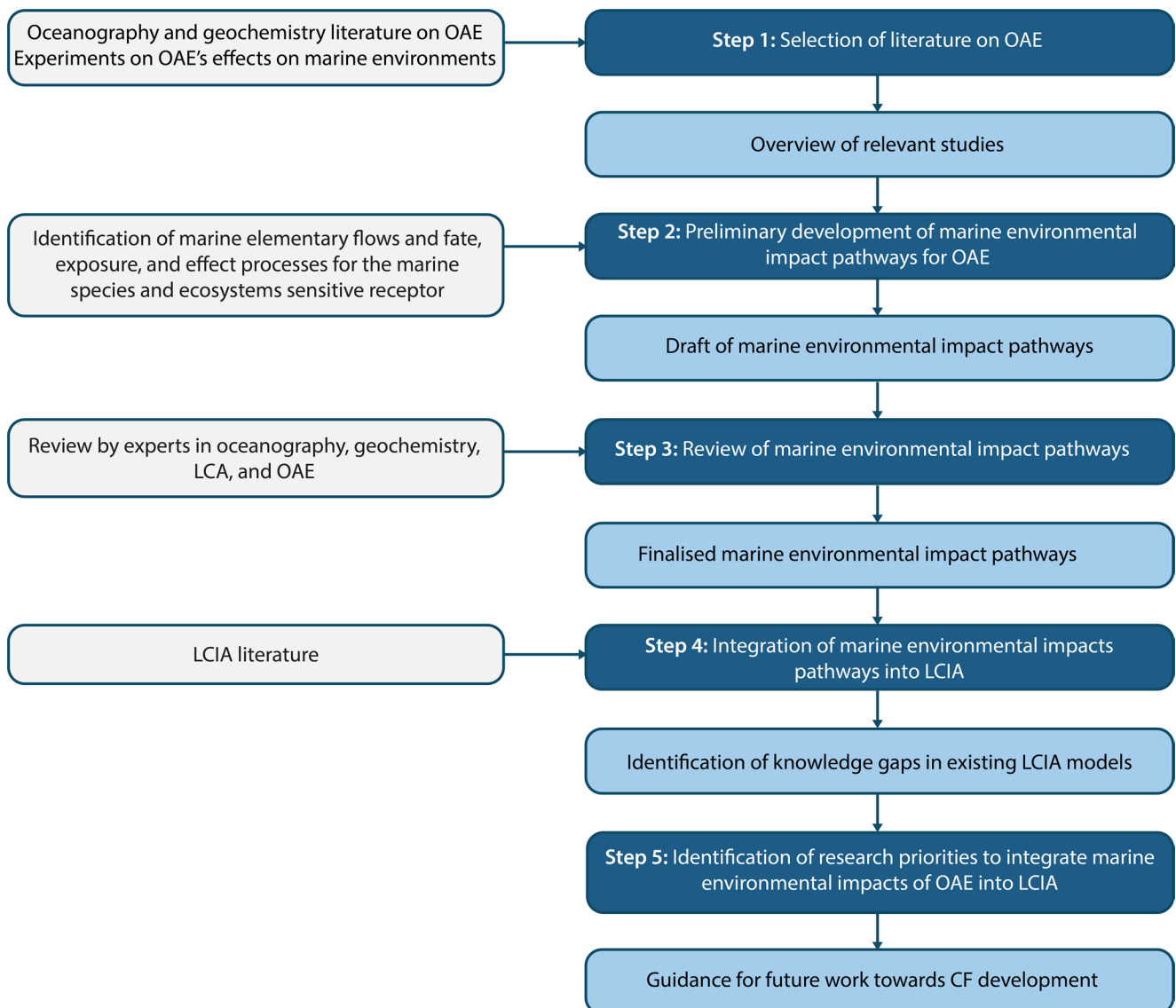


Fig. 1 Overview of the methodological approach. Adapted from Woods et al. (2021) and Richter et al. (2024). The phases of the approach are in dark blue, the required elements for each phase in grey, and the outcome of each phase in light blue

3.2 Step 1: selection of relevant literature

We reviewed the relevant oceanography and geochemistry literature on OAE and its impacts on marine species and ecosystems, using Scopus and Web of Science. We used a combination of broad search terms, such as ‘*ocean alkalinity enhancement*’, ‘*alkaline mineral*’, and ‘*marine impacts*’, alongside more specific terms related to OAE technologies, including ‘*olivine*’ and ‘*trace metals*’, and our literature review includes publications available up to August 31st, 2025. From the resulting search results (>200 scientific articles), the most cited or the most relevant articles based on the abstract were selected. Some additional articles were found as cited in the selected literature or recommended by co-authors with expertise in oceanography and OAE.

Lastly, one article was suggested by a reviewer during the reviewing process of the manuscript. In total, approximately 75 scientific articles were selected for Step 2.

3.3 Step 2: identification of the marine environment impact pathways

From the selected literature, we identified the key elements for the marine environmental impact pathways of OAE. These include elementary flows in the LCI released to the marine environmental compartment, the fate processes, the exposure processes, and the effect processes. From these identified processes, the impact pathways were developed.

Ocean alkalinity enhancement life cycle

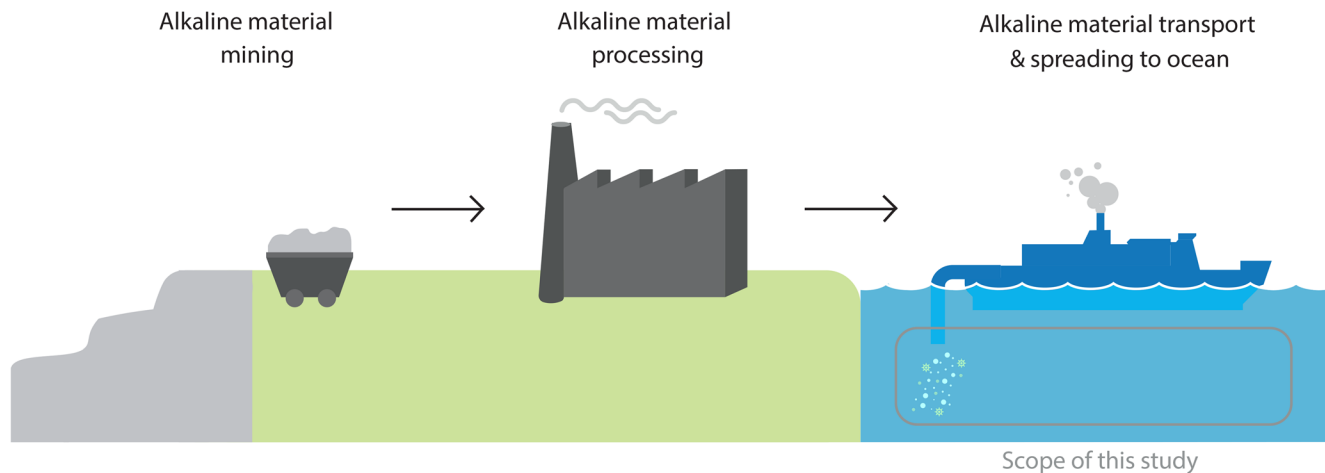


Fig. 2 Schematic representation of the general ocean alkalinity enhancement (OAE) life cycle. We look specifically at the marine environmental impacts resulting from alkaline material addition to the ocean

Table 1 Types of alkaline materials used in different alkalinity enhancement methods, along with their corresponding deployment (i.e., addition) sites.

Alkaline material	Method	Location	References
CaO, Ca(OH) ₂	Ocean liming	Open ocean at the mixed surface layer	Oschlies et al. (2025)
	Coastal enhanced weathering (CEW)	Coastal waters, eventually in wastewater treatment plant outflows	Campbell et al. (2022); Oschlies et al. (2025)
Silicate rocks and minerals (e.g., olivine, dunite, basalt), carbonate rocks and minerals (e.g., CaCO ₃ , ikaite), anthropogenic material (e.g., steel slag), Mg(OH) ₂	OAE using other alkaline materials	Open ocean at the mixed surface layer	Bach et al. (2019); Renforth et al. (2022); Oschlies et al. (2025)
	CEW using other alkaline materials	Coastal waters	Bach et al. (2019); Campbell et al. (2022); Renforth et al. (2022); Oschlies et al. (2025)
CaCO ₃	Enhanced benthic weathering (EBW)	Onto marine sediments, coastal or offshore	Fuhr et al. (2023, 2025); Dale et al. (2024).
Bases (e.g., NaOH)	Electrochemical approaches	Coastal waters	Ringham et al. (2024); Oschlies et al. (2025)

3.3.1 Identification of marine elementary flows

For OAE, the main exchange between the product system and the marine environment is the intentional addition of alkaline material to the ocean to provide CDR (NASSEM

2022; Eisaman et al. 2023; Oschlies et al. 2025). Depending on the specific OAE approach, alkaline material is typically added to the open ocean at the sea surface or to coastal waters (Renforth and Henderson 2017; He and Tyka 2023; Lindland et al. 2025), and there have been suggestions to directly add it onto marine sediments in coastal areas or offshore (Fuhr et al. 2023, 2025; Dale et al. 2024).

OAE can use various alkaline materials (Table 1). Quicklime (CaO) or hydrated lime (Ca(OH)₂) obtained from limestone have been widely studied (Caserini et al. 2022; Moras et al. 2022; Kowalczyk et al. 2024). Other alkaline materials can also be used, such as pulverised silicate minerals (e.g., olivine), pulverised carbonate minerals (e.g., calcite (CaCO₃)), waste or by-product materials obtained from human activities (e.g., steel slags), or magnesium hydroxide (Mg(OH)₂) (Bach et al. 2019; Renforth et al. 2022; Yang et al. 2023). Bases (e.g., sodium hydroxide (NaOH)) isolated from pumped seawater or brine are also potential candidates (Ringham et al. 2024; Oschlies et al. 2025).

Additional elementary flows may enter the marine environment through alkaline material addition (Table 2). The dissolution of some alkaline materials, such as steel slag or olivine, can release trace metals, with the types and quantities varying depending on the composition and purity of the alkaline mineral (Renforth and Henderson 2017; Guo et al. 2024). Additionally, essential nutrients and ions may be co-released (Bach et al. 2019).

3.3.2 Identification of fate processes

Alkaline material and its co-released elements move away from the location of addition through four transport mechanisms: diffusion, advection, mixing, and sinking. Diffusion

Table 2 Potential co-released elements during the dissolution of different alkaline materials. The elements listed are among the most reported in the ocean alkalinity enhancement (OAE) literature; however, this list may not be exhaustive, and other elements could be co-released as new alkaline materials are explored for OAE.

Potential co-released element	Alkaline material	References
Trace metals		
Aluminium (Al)	Steel slag	Moras et al. (2024)
Cobalt (Co)	Olivine, steel slag	Moras et al. (2024); Zhuang et al. (2025)
Chromium (Cr)	Olivine, steel slag	Bach et al. (2019); Moras et al. (2024); Zhuang et al. (2025)
Copper (Cu)	Steel slag	Moras et al. (2024)
Iron (Fe)	CaO, Ca(OH) ₂ , Mg(OH) ₂ , olivine, steel slag	Mayes et al. (2008); Renforth and Henderson (2017); Bach et al. (2019); Dupont and Metian (2023); Guo et al. (2024)
Manganese (Mn)	Steel slag	Guo et al. (2024); Moras et al. (2024)
Molybdenum (Mo)	Steel slag	Mayes et al. (2008); Bach et al. (2019)
Lead (Pb)	Steel slag	Bach et al. (2019); Moras et al. (2024)
Nickel (Ni)	Some silicate rocks and minerals (e.g., olivine, dunite), some carbonate rocks and minerals (e.g., CaCO ₃), steel slag	(Montserrat et al. 2017; Bach et al. 2019; Flipkens et al. 2021; Guo et al. 2024; Moras et al. 2024)
Vanadium (V)	Steel slag	Mayes et al. (2008)
Zinc (Zn)	Steel slag	Moras et al. (2024)
Essential nutrients and ions		
Calcium ion (Ca ²⁺)	CaO, Ca(OH) ₂ , some carbonate rocks and minerals (e.g., CaCO ₃ and ikaite), silicate rocks and minerals, steel slag	Bach et al. (2019); Dupont and Metian (2023); Eisaman et al. (2023); Guo et al. (2024)
Dissolved silicate (DSi)	CaO, Ca(OH) ₂ , Mg(OH) ₂ , silicate rocks and minerals, steel slag	Renforth and Henderson (2017); Bach et al. (2019); Guo et al. (2024, 2025)
Magnesium ion (Mg ²⁺)	CaO, Ca(OH) ₂ , carbonate rocks and minerals, Mg(OH) ₂ , some silicate rocks and minerals (e.g., olivine, basalt), steel slag	Dupont and Metian (2023); Eisaman et al. (2023); Guo et al. (2024)
Phosphate (PO ₄ ³⁻)	Steel slag	Guo et al. (2024, 2025)

is the transport of molecules driven by concentration gradients, occurring slowly and at small spatial scales. Transport by ocean circulation includes (i) advection, which redistributes material through current-driven flow, and (ii) turbulent mixing, generated by winds, waves, and shear, which enhances dispersion and dilution. Sinking refers specifically

to downward transport to deep ocean layers. These processes can occur in any oceanic zone depending on the location of addition (Bach et al. 2019).

Another important fate process is the dissolution of the alkaline material. Addition in the open ocean results in dissolution within the mixed surface layer (Kowalczyk et al. 2024), whereas addition in coastal waters results in partial dissolution in seawater and in pore waters from coastal sediments (Mendes et al. 2025). Lastly, after solid alkaline material settles from the water column into the sediments, it can become buried. When the material is added directly onto sediments, most is buried and remains undissolved (Dale et al. 2024).

In the SI (Section C), we describe for each fate process its effect on the residence time of the alkaline material and identify the main factors influencing the process. However, alkaline material fate in seawater has been mostly studied in controlled laboratory environments, which do not reflect natural conditions (Meysman and Montserrat 2017; Flipkens et al. 2023). More in situ experiments are needed to increase our understanding of these fate processes.

3.3.3 Identification of exposure processes

Marine species and ecosystems are expected to be primarily and directly exposed to the altered seawater conditions induced by alkalinity addition, which include an increase in pH and a decrease in seawater partial pressure of CO₂ (Bach et al. 2019; Ocean Visions 2022). These chemical changes would be temporary but likely pronounced adjacent to the location of addition, depending on the speed at which seawater mixes and re-equilibrates with the atmosphere (Renforth and Henderson 2017; Bach et al. 2019; Liu et al. 2025). However, in this particular case, the boundary between fate and exposure may be ambiguous, as changed ocean chemistry represents both the propagation of the stressor and the condition experienced by organisms, and may therefore be more properly handled as a single combined fate-exposure process.

Another exposure process could be via unintended ingestion of alkaline material by grazers and filter feeders, thereby also getting exposed to the potentially contained trace metals and essential nutrients and ions (Harvey 2008; NASEM 2022; Flipkens et al. 2023). In particular, trace metals can biomagnify through the food chain and reach higher trophic levels (Bach et al. 2019). Lastly, alkaline material added could increase turbidity, which would affect light availability in the photic zone as well as induce a ‘white water’ phenomenon that could impair predators’ visibility, such as fish and seabirds (NASEM 2022), but research on this visual exposure route is lacking.

3.3.4 Identification of effect processes

Changes in ocean chemistry from added alkalinity could lead to immediate effects on marine species, notably toxic effects. For instance, the temporary but substantial shift in the carbonate system combined with CO₂ reduction is likely to affect primary producers like phytoplankton with potential cascading effects on entire marine ecosystems (Renforth and Henderson 2017). However, recent research shows mostly insignificant effect post-alkalinity addition on pelagic low-trophic-level species (Table 3). Overall, these results indicate relatively good physiological tolerance of these species to added alkalinity as well as good community resistance at these trophic levels.

Another important effect of OAE-driven ocean chemistry shift and associated pH increase is the counteraction of ocean acidification (Hartmann et al. 2023). Mitigating acidification would facilitate the calcification mechanism and thus benefit calcifying organisms (Bach et al. 2019). Nevertheless, a minority of calcifying species may experience adverse effects from alkalinity addition (Bednaršek et al. 2025).

Enhanced calcification from OAE can also trigger unintended calcium carbonate (CaCO₃) precipitation, a process that consumes alkalinity and releases CO₂ into surrounding waters (Moras et al. 2022). The primary consequence is a reduction in CDR efficiency (Hartmann et al. 2023), but it may also exacerbate ocean acidification and cause turbidity (Ringham et al. 2024; Jones et al. 2025).

Additionally, co-released OAE products can cause toxic effects on marine species and ecosystems. While trace metals naturally occur in seawater at low concentrations, they may become harmful when present at elevated levels (Kwong 2024). These metals can bioaccumulate in organisms and biomagnify through the food chain (Anandkumar et al. 2018; Bach et al. 2019). Recent studies have begun to explore these toxic effects (Table 4). Beyond trace metals, co-released nutrients and ions may also cause toxic effects when present in high amount. For example, calcium ion (Ca²⁺) release in quicklime-based OAE can be harmful, as keeping low intracellular Ca²⁺ is essential but metabolically costly (Bach et al. 2019).

Co-released products from OAE can also drive eutrophication by enriching the local environment, giving more sensitive phytoplankton species a growth advantage and potentially leading to bloom and alteration of communities' composition. For instance, diatoms, often limited by dissolved silicate (DSi), can benefit from DSi-based OAE, potentially shifting phytoplankton communities toward diatom dominance (Bach et al. 2019; Oschlies et al. 2025). Such eutrophication effects have been mainly observed in studies involving steel slag and olivine (Table 4).

Nonetheless, OAE effects on marine species remain insufficiently understood, prompting scientists to call for further research. This includes studies on higher trophic levels, such as fish (Ferderer et al. 2022), and on other species groups, like calcifiers (Sánchez et al. 2024), at the community level (Britton et al. 2025), and across different marine biomes (Xin et al. 2024), including benthic environments (Jones et al. 2025). Future experiments should also examine seasonal variability (Ren et al. 2025), varying OAE technologies and intensities, and unequilibrated conditions following OAE application (Flipkens et al. 2023; Sánchez et al. 2024). Long-term studies are particularly important for capturing multi-generational effects (Bhaumik et al. 2025). Lastly, more research is needed on the effects of trace metal co-release (Xin et al. 2024; Zhuang et al. 2025).

3.3.5 Marine environmental impact pathways

From the information on the LCI marine elementary flows and the fate, exposure, and effect processes, we identified the pathways of OAE's marine environmental impacts (Fig. 3). The identified pathways can be associated with three marine impact categories: marine ecotoxicity, marine eutrophication, and ocean acidification. The impact pathways for each impact category are presented individually in the SI (Section D).

3.4 Step 3: review of the marine environment impact pathways

The impact pathways derived from the literature were subsequently completed and revised through internal review by co-authors with expertise in either LCIA or oceanography and OAE, and through feedback from external OAE experts during a workshop held at the general assembly of the EU-funded SEAO2-CDR (Strategies for the Evaluation and Assessment of Ocean-based Carbon Dioxide Removal) project, a European Union's Horizon Europe research programme on mCDR approaches, in June 2025. The group of experts was selected based on the relevance of their expertise for this topic, either in LCA ($n = 6$) or in oceanography and OAE ($n = 8$).

3.5 Step 4: analysis of the marine environmental impact pathways integration into LCIA models

We reviewed the LCIA modelling literature to determine which components of the identified OAE marine environmental impact pathways are already represented in existing LCIA models, and which remain unaddressed. This was done for each marine impact category identified as relevant to OAE: marine ecotoxicity, marine eutrophication, and

Table 3 Ocean alkalinity enhancement (OAE) experiments on the effects of added alkalinity on marine species and ecosystems

Reference	Experiment	Species group	Alkaline material	Effects*
Antoni et al. (2025)	Field, mesocosm	Pelagic, bacterial community	Ca(OH) ₂	No effect on community structure under unequilibrated** moderate and intense OAE.
Bhaumik et al. (2025)	Laboratory	Pelagic, zooplankton copepods (<i>Temora longicornis</i>)	Ca(OH) ₂	Negative effect on respiratory and digestion rates as well as negative effect on phytoplankton prey (<i>Rhodomonas salina</i>) availability but positive effect on prey nutritional quality, hence effect on predator considered to be mitigated, under unequilibrated and varying intensity of OAE.
Britton et al. (2025)	Laboratory	Benthic, kelp (<i>Ecklonia radiata</i>)	NaOH	No effect on physiology across life stages under unequilibrated and varying intensity of OAE, except a negative effect on growth rate on all life stages under unequilibrated intense OAE.
Camatti et al. (2024)	Laboratory	Pelagic, copepod (<i>Acartia tonsa</i>)	Ca(OH) ₂	No effect on physiology under short-term exposure at unequilibrated moderate OAE. Negative effect on survival rate under long-term exposure at unequilibrated intense OAE.
De Castro et al. (2025)	Laboratory	Pelagic, phytoplankton and bacterial community	CaO	Negative effect on development but no effect on community composition for phytoplankton, order-specific effect abundance but no effect on community composition for bacteria under unequilibrated moderate OAE.
Delacroix et al. (2024)	Laboratory	Pelagic, phytoplankton (<i>Tetraselmis suecica</i>)	Ca(OH) ₂	Negative effect on survival rate under unequilibrated and equilibrated moderate OAE.
			Mg(OH) ₂	No effect on growth and survival rate under unequilibrated and equilibrated moderate OAE.
Gately et al. (2023)	Laboratory	Pelagic, phytoplankton calcium carbonate producer (<i>Emiliana huxleyi</i>) and silica producer (<i>Chaetoceros</i> sp.)	Na ₂ CO ₃ + CaCl ₂ H ₄ O ₂	No effect on physiology under equilibrated moderate and intense OAE.
Goldenberg et al. (2024)	Field, mesocosm	Pelagic and demersal, juvenile fish (<i>Clupea harengus</i> , <i>Gadus morhua</i>)	Ca(OH) ₂	No effect on growth and survival rate, positive effect on biomass under unequilibrated intense OAE.
Gore et al. (2019)	Laboratory	Benthic, red calcifying algae (<i>Corallina</i> spp.)	Na ₂ CO ₃	Small effect on primary productivity and respiration rates, and photophysiology under unequilibrated moderate OAE.
Guo et al. (2025)	Laboratory, ship-based mesocosm	Pelagic, phytoplankton community	NaOH	Small effect on physiology under unequilibrated moderate OAE.
Jones et al. (2025)	Laboratory	Benthic, gastropod mollusk (<i>Phyllaplysia taylori</i>) and isopod (<i>Idotea resicata</i>)	NaOH	Negative effect on survival rate under unequilibrated intense OAE.
Kousoulas et al. (2025)	Laboratory, microcosm	Phytoplankton and zooplankton community	NaOH	Effect on community composition and delayed bloom under unequilibrated intense OAE, but considered small compared to climate benefit.
			NaOH + NaHCO ₃	Small effect on community composition under equilibrated moderate OAE.
Marín-Samper et al. (2024)	Field, mesocosm	Pelagic, phytoplankton community	NaHCO ₃ + Na ₂ CO ₃	No effect on community metabolism or composition under equilibrated moderate and intense OAE. Positive effect on primary production under equilibrated moderate OAE.
Nocera et al. (2025)	Laboratory, mesocosm	Pelagic, zooplankton community	Ca(OH) ₂	Small effect on species abundance and community structure under short-term exposure at unequilibrated moderate and intense OAE.
Oberlander et al. (2025)	Laboratory	Pelagic, phytoplankton (<i>Thalassiosira pseudonana</i> , <i>Diacronema lutheri</i>)	NaOH	Small effect on viability and growth rates under short-term exposure at unequilibrated intense OAE. Negative effect on growth rate under long-term exposure at unequilibrated intense OAE.

Table 3 (continued)

Reference	Experiment	Species group	Alkaline material	Effects*
Paul et al. (2025)	Field, mesocosm	Pelagic, phytoplankton community	$\text{NaHCO}_3 + \text{Na}_2\text{CO}_3$	No effect on biomass nor bloom occurrence and magnitude, as well as no effect on most biogeochemical pools under short-term and long-term exposure at equilibrated moderate and intense OAE.
Ramírez et al. (2025)	Field, mesocosm	Pelagic, phytoplankton community	$\text{NaHCO}_3 + \text{Na}_2\text{CO}_3$	Small effect on physiology under equilibrated moderate and intense OAE.
Sánchez et al. (2024)	Field, mesocosm	Pelagic, zooplankton community	$\text{NaHCO}_3 + \text{Na}_2\text{CO}_3$	Negative effect on reproduction and productivity rates under short-term exposure at equilibrated moderate and intense OAE, probably trophically mediated.
Subhas et al. (2022)	Field, microcosm incubation	Pelagic, microbial community	$\text{NaHCO}_3, \text{Na}_2\text{CO}_3$	Small effect on biological calcification and net primary production rates under equilibrated moderate and intense OAE.
Traboni et al. (2025)	Laboratory, mesocosm	Pelagic, plankton community	Ca(OH)_2	Small effect on community composition and survival rates and no effect on growth and grazing rates under unequilibrated moderate and intense OAE.
Xin et al. (2024)	Field, mesocosm	Pelagic, phytoplankton and microzooplankton community	$\text{HCO}_3^- + \text{CO}_3^{2-}$	No effect on abundance and biomass under equilibrated moderate and intense OAE.

*Effects are noted as small when the study reported them as noticeable but statistically non-significant. Negative effects refer to an adverse response (e.g., reduced survival growth or community productivity), whereas positive effect indicates a beneficial response (e.g., enhanced growth, biomass, or productivity) relative to the control

**Equilibrated: seawater has reached chemical balance with atmospheric CO_2 . Unequilibrated: seawater is still exchanging CO_2 with atmosphere and has not yet reached balance

ocean acidification (Fig. 4a). We examined LCIA method families as implemented in ecoinvent (v3.11), as this is the most widely used LCI database for OAE LCA case studies (Delval et al. 2025), as well as other method families not included in ecoinvent and characterisation models that have not yet been incorporated into any LCIA method family.

3.5.1 Marine ecotoxicity

Marine ecotoxicity refers to the potential damages of toxic substances discharged to marine environments (Carvalho et al. 2024). Two LCIA method families in ecoinvent cover this impact category: CML (v4.8) at the midpoint level and ReCiPe (v1.03) at the midpoint and endpoint levels. Two other method families not integrated in ecoinvent exist for marine ecotoxicity at the endpoint level, which are LC-IMPACT and IMPACT World+ (v2.1, expert version, 2024). Lastly, additional characterisation models were developed (e.g., Dong et al. 2016, 2018), but they are not integrated into any LCIA method family. For a detailed overview of how marine ecotoxicity is addressed in LCIA models, please refer to the SI (Section E.I).

We identified several gaps in these models that do not allow to properly assess marine ecotoxicity potentially caused by OAE in LCA. Regarding LCI elementary flows, a first limitation is that some LCIA models do not characterise all the metals identified in Sect. 3.3.1 as potential flows released in marine environments by this technology. For example, CML and ReCiPe do not characterise the

ecotoxicity of aluminium (Al), Fe, and manganese (Mn), and the model developed by Dong et al. (2016, 2018) omits Al, molybdenum (Mo), and vanadium (V). Only the models in LC-IMPACT and IMPACT World+ provide a coverage of metals potentially co-released by OAE. Moreover, no marine ecotoxicity model accounts for nutrients or alkaline materials as elementary flows.

Concerning the fate processes, the models vary considerably with respect to marine spatial resolution. CML and ReCiPe divide the ocean into only three broad climate zones, which oversimplifies its spatial heterogeneity. Dong et al. (2016, 2018) use 64 LMEs, but these are restricted to coastal areas, reducing the applicability of the model to coastal OAE assessments. LC-IMPACT and IMPACT World+ provide the most comprehensive coverage and regionalisation, partitioning the marine environment into nine oceanic and 33 coastal regions (Kounina et al. 2014; Carvalho et al. 2024), but they do not characterise direct emissions to the open ocean. Conversely, OAE activities may release toxic substances directly into offshore marine waters, requiring adapted fate models. Moreover, LC-IMPACT and IMPACT World+ do not differentiate oceanic depth zones and thus cannot represent fate mechanisms like sinking and burial.

In relation to the exposure processes, the exposure mechanism for alkaline materials would differ fundamentally from those in current marine ecotoxicity models. While current models typically assess toxicity based on the bioavailability of a substance once released in an environment (Hauschild and Huijbregts 2015), alkaline materials would primarily

Table 4 Ocean alkalinity enhancement (OAE) experiments on the effects of co-released products on marine species and ecosystems

Reference	Experiment	Species group	Alkaline material	Effects
Ferderer et al. (2024)	Field, mesocosm	Plankton community	$\text{MgCl}_2 \cdot 6\text{H}_2\text{O} + \text{Na}_2\text{SiO}_3 \cdot 5\text{H}_2\text{O}$	Fertilisation of diatom community due to nutrient release (DSi).
Flipkens et al. (2023)	Laboratory	Benthic, amphipod (<i>Gammarus locusta</i>)	Olivine	Negative effect on survival, growth, and reproduction rates due to trace metal bioaccumulation (Cr and Ni).
Goldenberg et al. (2024)	Field, mesocosm	Pelagic and demersal, juvenile fish (<i>Clupea harengus</i> , <i>Gadus morhua</i>)	Olivine	No effect on growth and survival rates due to nutrient release (DSi).
Guo et al. (2024)	Laboratory, microcosm	Plankton community	Steel slag	Limited effect on abundance and community composition due to nutrient (PO_4^{3-} and Si) and trace metal (Mn and Fe) release.
			Olivine	Positive effect on abundance and effect on community composition due to nutrient (DSi) and trace metal (Fe and Ni) release.
Guo et al. (2025)	Laboratory, ship-based mesocosm	Pelagic, phytoplankton community	NaOH	No nutrient and limited trace metal release and no effect observed.
			Steel slag	Positive effect on growth rate for nano- and microeukaryotes while negative effect on survival rate in another phytoplankton group (<i>Prochlorococcus</i>) due to high trace metal release (Al, Fe, and Mn), overall altering community composition. Nutrient release (PO_4^{3-} and Si) also observed.
			Olivine	Negative effect on survival rate in some phytoplankton groups (<i>Prochlorococcus</i> , <i>Synechococcus</i> , and picoeukaryote) due to high trace metal release (Al, Co, Cu, Mn, and Ni). Nutrient release (DSi) also observed.
Hutchins et al. (2023)	Laboratory	Pelagic and benthic, phytoplankton (<i>Nitzschia</i> , <i>Ditylum</i> , <i>Emiliana</i> , <i>Trichodesmium</i> , <i>Crocospaera</i> , <i>Synechococcus</i>)	Olivine	Small effect on physiology, positive effect on growth rate for some taxa in specific conditions due to nutrient release (Fe and DSi).
Jankowska et al. (2024)	Laboratory	Benthic, invertebrate amphipod (<i>Leptocheirus plumulosus</i> , <i>Eohaustorius estuarius</i>), polychaete (<i>Neanthes arenaceodentata</i> , <i>Alitta virens</i>), bivalve (<i>Macoma nasuta</i>)	Olivine	No effect on survival and growth rates due to trace metal accumulation (Ni).
(Li et al. 2024)	Laboratory	Pelagic, phytoplankton (<i>Gephyrocapsa oceanica</i> , <i>Thalassiosira pseudonana</i> , <i>Phaeodactylum tricornutum</i>)	Olivine	Positive effect on growth for highly silicified diatoms (<i>T. pseudonana</i>) due to nutrient release (DSi).

cause toxic impacts through changes in ocean chemistry, requiring a different exposure model than for trace metals.

As for the effect processes, models for toxicity from trace metals are already well integrated in LCIA, but often rely on freshwater toxicity data due to the limited availability of risk assessment data on marine species (Fantke et al. 2018), which incorrectly implies a direct correlation between marine and freshwater ecotoxicity (Carvalho et al. 2024). Dong et al. (2016, 2018) is the only model to rely exclusively on toxicity data for marine species. Moreover, alkaline materials or nutrients could potentially cause toxicity in marine species (Renforth and Henderson 2017; Bach

et al. 2019) for which effect models are lacking, but this link has not yet been conclusively established.

3.5.2 Marine eutrophication

Marine eutrophication refers to the marine ecosystem response to increased inputs of nutrients or organic matter (Cosme and Hauschild 2017). Two LCIA method families in ecoinvent include marine eutrophication as an impact category: EF (v3.1) at the midpoint level and ReCiPe (v1.03) at the midpoint and endpoint levels. Three additional method families not included in ecoinvent also cover marine

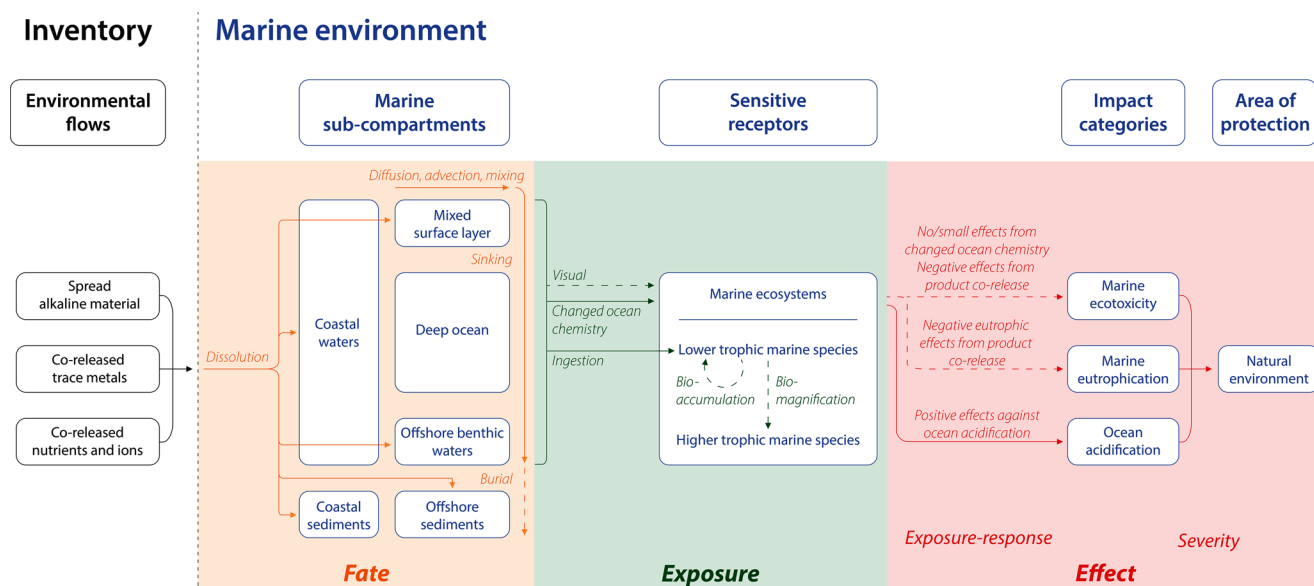


Fig. 3 Marine environmental impact pathways of ocean alkalinity enhancement (OAE). Solid arrows indicate established linkages, while dashed arrows represent uncertain or currently under-researched connections based on the present state of knowledge. (Note that a visual

exposure process has been proposed in the scientific literature as explained in Sect. 3.3.3, but it has not yet been linked to any effect processes due to insufficient research.)

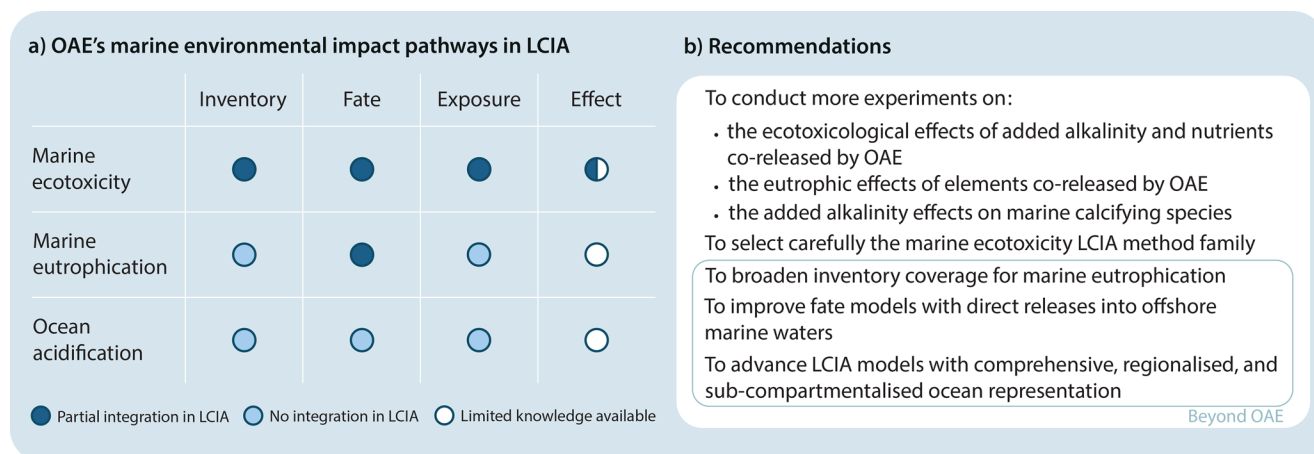


Fig. 4 Guidance for better integrating ocean alkalinity enhancement (OAE)'s marine environmental impacts in life cycle impact assessment (LCIA) models. **(a)** Summary of current integration of OAE's marine environmental impact pathways in LCIA models. Inventory refers to the elementary flows in the LCI that were identified to be

eutrophication: IMPACT World+ at the midpoint and endpoint levels, LC-IMPACT at the endpoint level, and TRACI (v2.2) at the midpoint level. Lastly, one marine eutrophication characterisation model (Henryson et al. 2018) is not integrated into any LCIA method family. For a detailed overview of how marine eutrophication is addressed in LCIA models, please refer to the SI (Section E.II).

With respect to LCI elementary flows to the ocean, existing marine eutrophication models only characterise nitrogen (N) compounds. This reflects the origin of eutrophication modelling, which was developed to assess eutrophication

connected to a particular marine impact category and the LCIA models of this impact category already characterise. Please refer to the SI, Section D, for further details on each process within marine environmental impact pathways. **(b)** Summary of recommendations for better integrating OAE's marine environmental impacts in LCIA models

from N and phosphorus (P) releases associated with fertiliser use, manure application, and fossil fuel combustion (Verones et al. 2020). Because marine waters are generally N-limited (EC-JRC 2012), LCIA modellers have focused their assessments solely on this nutrient for marine eutrophication (Struijs et al. 2009; Cosme et al. 2015; Huijbregts et al. 2017). However, other substances may also contribute to stimulating primary production, such as P, Fe, or DSi (Cosme et al. 2018; Browning and Moore 2023), with Fe and DSi identified as potentially released by OAE (Table 2). The only exception is the model by Henryson et al. (2018),

which also accounts for P compounds; however, the model is limited to Sweden in its geographical coverage.

Regarding fate processes, most marine eutrophication models are limited to coastal waters in terms of ocean's spatial resolution (Struijs et al. 2009; Cosme and Hauschild 2017). This restriction arises because eutrophication from agricultural runoff and fossil fuel combustion generally occurs near emission sources or from discharges from freshwater systems, leading offshore regions to be neglected during model development. When these models account for direct emission releases into marine waters (i.e., ReCiPe (v1.03), LC-IMPACT, and TRACI), it is specifically coastal marine waters (like LMEs) and not open-ocean waters. In contrast, OAE introduces nutrients directly into the ocean at the location of addition, which can be coastal or offshore. Consequently, eutrophication impacts resulting from offshore OAE deployments cannot be captured by these LCIA models. These limitations highlight the need for adapted fate modelling processes to adequately assess OAE-related marine eutrophication impacts.

Lastly, exposure and effect models are lacking for eutrophication impacts arising from other nutrients than N (e.g., DSi or Fe). Consequently, current models are unsuitable for comprehensive OAE assessments, where eutrophication impacts may arise from DSi or Fe. Before such models are developed, the causation link between OAE development and eutrophic effects must be further validated by laboratory and mesocosm experiments.

3.5.3 Ocean acidification

Ocean acidification refers to the oceanic uptake of anthropogenic CO₂, lowering seawater pH, reducing carbonate ion concentration, and weakening the ocean's buffering capacity, collectively impairing calcification and other physiological functions in marine organisms (Orr et al. 2005). Although this impact category is not yet included in any method family available inecoinvent, important progress has been made over the past decade to develop ocean acidification modelling within LCIA. IMPACT World+ includes an ocean acidification impact category and several characterisation models were recently developed (Scherer et al. 2022; Anderson et al. 2025). For a detailed overview of how ocean acidification is addressed in LCIA models, please refer to the SI (Section E.III).

Regarding OAE, characterisation models do not allow to capture its beneficial impact on ocean acidification. Current ocean acidification models focus their characterisation on elementary flows that contribute to ocean acidification (currently CO₂, carbon monoxide (CO), and methane (CH₄)), which lead to a decrease in seawater pH. In contrast, OAE counteracts ocean acidification by an impact pathway

fundamentally different in LCI elementary flows as well as fate and exposure processes. This technology releases alkaline material to seawater, enhancing total alkalinity and buffering capacity, thereby increasing seawater pH and increasing carbonate ion availability. This important difference means that current LCIA models cannot account for the beneficial impacts of OAE to mitigate ocean acidification.

3.6 Step 5: guidance on integrating marine environmental impacts into life cycle impact assessment

Comparing OAE marine environmental impact pathways with existing LCIA models revealed key research gaps in OAE assessments within LCA. We formulated recommendations for assessing OAE and outlined research priorities to improve the integration of OAE marine environmental impacts within marine ecotoxicity, marine eutrophication, and ocean acidification impact categories, as well as to enhance the ocean's spatial resolution in LCIA models. Addressing these research gaps is fundamental to the development of sub-compartmentalised and regionalised CFs for marine impact categories relevant to OAE. These recommendations are summarised in Fig. 4b.

3.6.1 Conducting more experiments on the marine environmental effects of OAE-induced ocean chemistry changes and co-product release

Additional experiments are needed to establish whether nutrient enrichment and increased alkalinity result in ecotoxicological effects on marine species before such processes can be integrated into characterisation models of the marine ecotoxicity impact category. Improving LCIA method families also requires additional marine toxicity data to derive appropriate effect factors instead of relying on freshwater toxicity data. Similar conclusions can be drawn for the marine eutrophication impact category; further experimental research is needed to determine the extent of eutrophic effects caused by elements co-released during OAE before developing adapted fate models.

Regarding the ocean acidification impact category, adapted characterisation models are required to capture the counteracting impact of OAE on marine acidification. This modelling effort should start with the development of species sensitivity distributions (SSDs) to quantify species responses to increased alkalinity, elevated pH, and lower dissolved CO₂, analogous to what has already been done for decreased pH (Azevedo et al. 2015; Bednaršek et al. 2025; Anderson et al. 2025). Such SSDs can only be developed once sufficient experiments are available that evaluate added alkalinity effects from OAE on a broad range of

marine calcifying species (e.g., corals, coccolithophores, molluscs, foraminifera, and calcareous algae). Establishing such SSDs would benefit from standardised experiment protocols to ensure comparability across studies. Capturing ecosystem-scale effects from OAE requires, however, complementary modelling frameworks beyond SSD-based characterisation.

3.6.2 Selecting an appropriate LCIA method family for assessing marine ecotoxicity

We recommend following the guidance of Carvalho et al. (2024), who compared existing characterisation models for marine ecotoxicity. The model integrated into the LC-IMPACT method family characterises a broad range of LCI elementary flows and emission compartments, and implements ecotoxicity modelling recommendations from USEtox (Rosenbaum et al. 2008). It also offers comprehensive coverage of metals potentially released by OAE and a regionalised marine compartment. IMPACT World+ provides a comparable metal coverage and ocean representation. The midpoint model of Dong et al. (2016, 2018) may be appropriate for coastal OAE cases where the alkaline material is known to potentially release one or more of the nine trace metals the model characterises. In contrast, ReCiPe or CML are not recommended, as their underlying models poorly represent metal behaviour (Carvalho et al. 2024), and they do not characterise all metals relevant to OAE. Generally, marine ecotoxicity characterisation models vary considerably in spatial coverage, environment flows, and methodological assumptions, which can influence the LCA results. Ideally, two LCIA method families with two different models should be used and the influences on their results compared (Carvalho et al. 2024).

3.6.3 Broadening the coverage beyond nitrogen for the marine eutrophication impact category

For marine eutrophication, LCIA characterisation models should expand their coverage beyond N compounds to enable comprehensive assessments of OAE. Current models are well-suited to capture the primary driver of marine eutrophication (i.e., marine ecosystem response to N inputs in marine waters generally N-limited (EC-JRC 2012)), but do not account for other substances that OAE may release, such as Fe or DSi, which could also trigger eutrophication. Broadening characterisation of elementary flows would better reflect the complexity of marine ecosystems, which are not universally N-limited and may exhibit nutrient co-limitation (Cosme et al. 2018).

3.6.4 Improving fate models to account for direct emissions to offshore marine waters

Accurate OAE assessment in LCA will require adapted fate models for the marine ecotoxicity and marine eutrophication impact categories that can explicitly represent direct substance releases into offshore marine waters. Some existing models do not account for direct emission pathway to the marine compartment, and those that do rely on simplified or aggregated marine representations. These representations are either of low spatial resolution, insufficient to capture marine spatial heterogeneity, or account for direct emissions to coastal marine waters. The representation of the ocean in LCIA models, often restricted to coastal regions, reflects the origin of LCA modelling, which used to assess human activities occurring primarily on land (Woods et al. 2016), with impacts reaching the ocean mainly through runoff into coastal waters (EC-JRC 2010; Dong et al. 2016; Veà et al. 2024). However, with human activities expanding into offshore environments, modelling frameworks must be extended to include these regions.

3.6.5 Improving marine spatial resolution in LCIA models

The ocean's spatial heterogeneity must be better represented. Current LCIA models represent the ocean in an overly simplified manner. However, the ocean differs importantly in local conditions, such as primary productivity, temperature, salinity, and biodiversity, both across oceanic regions (e.g., Arctic Ocean and North Pacific Ocean) and oceanic depth zones (e.g., benthic and pelagic) (Piacenza et al. 2015; Ninove et al. 2016; Liu et al. 2021). This spatial variability in marine conditions can lead to different impacts locally on marine environments. Moreover, using an overly simplified marine compartment prevents differentiation between transport processes across marine sub-compartments and their corresponding exposure pathways (Hajjar et al. 2024). For OAE assessments, this level of spatial detail is crucial, as the identified OAE-related fate processes vary among sub-compartments and the environmental impact would differ in magnitude depending on the distance to the location of alkaline material addition.

To enable accurate assessments, LCIA models should be regionalised, by accounting for different oceanic regions, and sub-compartmentalised, by differentiating across coastal and offshore zones as well as across oceanic depth zones. Similar challenges have already been addressed in microplastics LCIA modelling (Hajjar et al. 2024), where a fate framework was proposed that divides the ocean horizontally (from the continental to the global scale) and vertically (with the beach, water surface, the water column, and sediments). This multi-dimensional approach aligns well

with the fate processes relevant for OAE and could serve as a basis for developing OAE-specific fate models, and more broadly, for improving the representation of ocean-related impacts in LCIA.

4 Discussion

4.1 Methodological contribution and research priorities for OAE assessment in LCIA

The methodological approach developed in this work enables the identification of marine environmental impact pathways of OAE, which requires combining the LCIA field with oceanography and engineering expertise. Our approach represents an initial phase toward the development of sub-compartmentalised and regionalised CFs for the identified marine environmental impacts in LCIA. Unlike many established LCIA methods, which often start from broadly defined stressor-endpoint relationships (e.g., ocean acidification leading to biodiversity loss), our approach starts from technology-specific marine elementary flows released directly into the marine compartment. Context-dependent LCIA developments are useful when the environmental mechanism depends strongly on release conditions and technological context. In such cases, meaningful CF developments involve the identification of elementary flows, including spatially and technology differentiated emissions, such as particulate matter (Oberschelp et al. 2020) or soil compaction (Stoessel et al. 2018). Similarly, marine technologies may benefit from this bottom-up, technology-driven approach, as their interactions with the marine environment are strongly influenced by release and deployment conditions.

We identified key research needs to enable a more comprehensive assessment of OAE within LCIA. Among the top research priorities, there is the need for additional in situ experiments to establish clear causality from added alkalinity and nutrient enrichment to potential ecotoxicological and eutrophication effects. Such experiments should also investigate the impacts of increased alkalinity on a broader range of marine calcifying species. Furthermore, there is a need to develop fate models for OAE that represent elementary flows as being directly released to the open ocean. These models should also capture the ocean's spatial heterogeneity more accurately, accounting for both coastal and offshore dynamics, as well as for different oceanic layers.

4.2 Broader implications for LCIA and the OAE research landscape

Importantly, several of the research gaps identified, such as a crude ocean representation in models, a lack of modelling of direct release to offshore marine waters, and the limited coverage of elementary flows for marine eutrophication, remain relevant beyond OAE assessments and addressing them would advance LCIA more broadly. Addressing these identified research gaps would allow for the development of more robust CFs.

Improving the assessment of OAE's marine environmental impacts within LCIA would also complement ongoing research efforts that aim to assess the overall environmental performance of OAE with LCIA. The primary function of OAE, like other mCDR technologies, is to remove atmospheric CO₂, and understanding how LCIA can help quantify net carbon removals is essential. As the global warming impact category was not found to directly connect to marine species and ecosystems as a sensitive receptor, this aspect is not the focus of the present research. Nevertheless, this is an active area of research; recent case studies notably evaluated how LCIA can be used to evaluate the net carbon removal potential of OAE, thereby contributing to reducing global warming (Foteinis et al. 2022, 2023; Yang and Feng 2026; Katish et al. 2026; Myridinas et al. 2026).

4.3 Limitations of the methodological approach

We acknowledge several limitations to this approach. The analysis focuses specifically on marine environmental impact pathways, although other sensitive receptors, like humans or structures with instrumental or cultural value (e.g., fisheries zones), may be impacted by OAE's deployment in marine environments. The impact pathways for these receptors are briefly addressed in the SI (Section B). Another limitation is that this approach does not address the temporal resolution of the identified marine environmental impacts. LCIA models are usually static, overlooking the temporality of environmental impacts. This issue has been identified for a long time in LCIA (Levasseur et al. 2010) and remains an active discussion in the LCIA community and an ongoing field of research (Fauzi et al. 2019).

4.4 Adapting the methodological approach to other marine technologies

Lastly, our proposed methodological approach for OAE could be adapted to other technologies deployed in and interacting with the ocean (i.e., marine technologies), including mariculture, maritime shipping, offshore wind farms, other mCDR approaches, submarine cables, desalination plants,

and deep-sea mining. In recent decades, human activities in marine environments have diversified and intensified, causing more widespread and severe anthropogenic pressures on marine ecosystems, driving their degradation and collapse (Halpern et al. 2019; Jouffray et al. 2020). Mitigating these stressors and their impacts is thus of utmost importance and requires, first, a clear understanding of their nature and magnitude. However, as with OAE, the assessment of marine environmental impacts associated with these technologies remains limited in LCA (Woods et al. 2016). Several marine impact categories remain insufficiently characterised or absent, such as seabed damage caused by deep-sea carbon storage (Rastelli et al. 2016), biotic resource depletion due to overfishing (Emanuelsson et al. 2014), and marine noise pollution from maritime shipping (Chahouri et al. 2022). Understanding the impact pathways through which these technologies affect marine environments is a necessary first step for their integration in LCIA models and for enabling more comprehensive environmental assessments of these technologies. Future research in this direction could build on the methodological approach developed in this work.

5 Conclusion

Our paper lays the groundwork for improving OAE's assessments in LCA by providing a methodological approach to identify OAE's marine environmental impact pathways and determine research priorities for comprehensively integrating these pathways in LCIA models. This methodological approach provides an initial phase toward the development of sub-compartmentalised and regionalised CFs. It includes five steps: (1) selecting oceanography and geochemistry literature on OAE and its impacts on marine ecosystems; (2) identifying the relevant marine elementary flows in the LCI and the fate, exposure, and effect processes; (3) reviewing by LCIA, oceanography, and technology experts; (4) analysing LCIA models to examine which elements of these marine environmental impact pathways are already represented in these models and which remain unaccounted for; (5) defining research priorities to improve the assessment of OAE's marine environmental impacts within LCA.

While we do not provide CFs due to important existing knowledge gaps, the framework yields five concrete analytical outputs, which together constitute a necessary precondition for any quantitative LCIA modelling of OAE:

- 1 A complete mapping of marine-relevant LCI elementary flows for OAE (i.e., alkaline materials and co-released trace metals, nutrients, and ions).
- 2 A technology-specific set of marine fate processes (i.e., diffusion, advection, mixing, sinking, burial, and dissolution).
- 3 A technology-specific linkage between these marine elementary flows and relevant marine impact categories (i.e., marine ecotoxicity, marine eutrophication, and ocean acidification).
- 4 A gap matrix showing which LCI marine elementary flows and associated impact categories are covered, and which components remain missing in existing LCIA methods.
- 5 A prioritised research agenda for CF development identifying what must still be developed.

Future research should operationalise the identified marine environmental impact pathways by translating them into quantitative fate, exposure, and effect models. As a next step, provisional CFs could be derived for selected LCI marine elementary flows where data availability is sufficient, allowing exploratory LCIA applications of OAE and providing an empirical basis to test, refine, and prioritise further model development. Furthermore, the methodological approach supports the systematic inclusion of qualitatively identified environmental concerns, thereby reducing the risk that potentially relevant impacts are excluded solely because quantitative characterisation methods are not yet available.

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Data availability All the data supporting the findings of this study are available within the paper and its Supplementary Information.

Declarations

Competing interests The authors declare no competing interests.

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