The International Journal of Life Cycle Assessment (2026) 31:134
https://doi.org/10.1007/s11367-026-02707-z

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

Mona H. Delval[1] · Patrik J. G. Henriksson[1,2] · Paul Behrens[1,3] · Laura Scherer[1] · Pablo Trucco-Pignata[4] · Patricia Grasse[5,6] · Phil Renforth[7] · Nils Thonemann[1]

Received: 8 January 2026 / Accepted: 25 June 2026 / Published online: 7 July 2026

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

Responsibile editor: Ian Vázquez-Rowe

Extended author information available on the last page of the article

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 (CO_2) 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 CO_2 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).

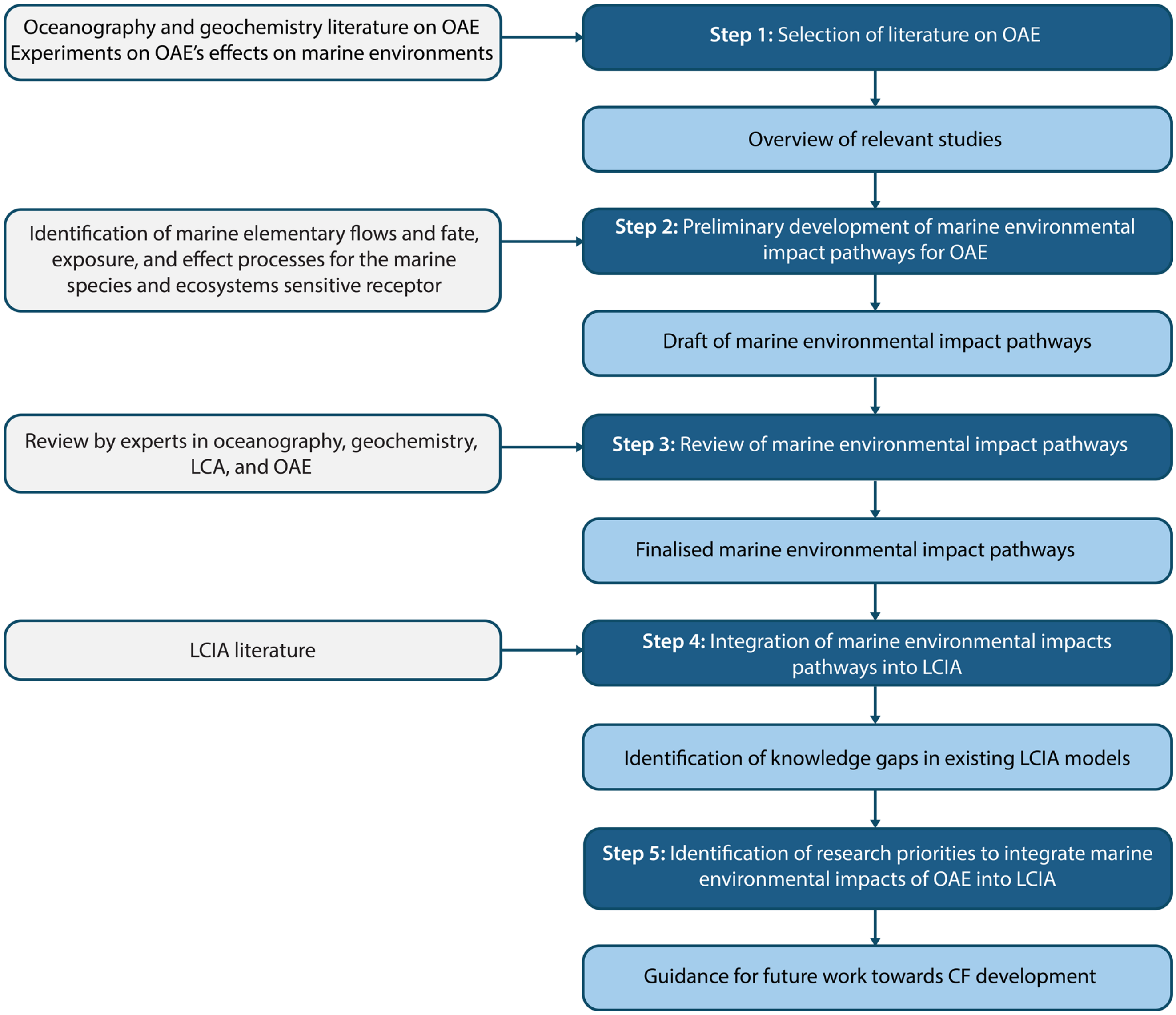

Fig. 1 Overview of the methodological approach. Adapted from Woods et al. (2021) and Richter et al. (2024). The phases of the approach are in dark blue, the required elements for each phase in grey, and the outcome of each phase in light blue

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.

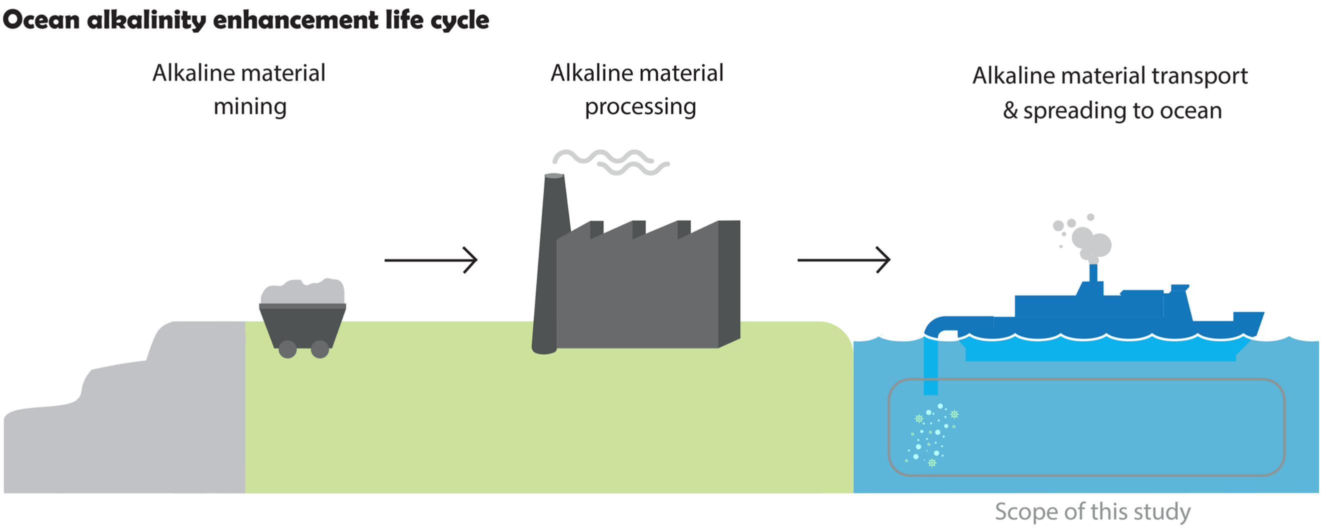

Fig. 2 Schematic representation of the general ocean alkalinity enhancement (OAE) life cycle. We look specifically at the marine environmental impacts resulting from alkaline material addition to the ocean

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 (NASEM 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 ($CaCO_3$)), 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 CO_2 (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 CO_2 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 ($CaCO_3$) precipitation, a process that consumes alkalinity and releases CO_2 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 (Ca^{2+}) release in quicklime-based OAE can be harmful, as keeping low intracellular Ca^{2+} 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 (*Temora longicornis*)	$Ca(OH)_2$	Negative effect on respiratory and digestion rates as well as negative effect on phytoplankton prey (*Rhodomonas salina*) 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 (*Ecklonia radiata*)	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 (*Acartia tonsa*)	$Ca(OH)_2$	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 (*Tetraselmis suecica*)	$Ca(OH)_2$	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 (*Emiliana huxleyi*) and silica producer (*Chaetoceros* sp.)	$Na_2CO_3 + CaCl_2H_4O_2$	No effect on physiology under equilibrated moderate and intense OAE.
Goldenberg et al. (2024)	Field, mesocosm	Pelagic and demersal, juvenile fish (*Clupea harengus, Gadus morhua*)	$Ca(OH)_2$	No effect on growth and survival rate, positive effect on biomass under unequilibrated intense OAE.
Gore et al. (2019)	Laboratory	Benthic, red calcifying algae (*Corallina* spp.)	Na_2CO_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 (*Phyllaplysia taylori*) and isopod (*Idotea resecata*)	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	$NaHCO_3 + Na_2CO_3$	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 (*Thalassiosira pseudonana, Diacronema lutheri*)	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	$NaHCO_3+Na_2CO_3$	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	$NaHCO_3+Na_2CO_3$	Small effect on physiology under equilibrated moderate and intense OAE.
Sánchez et al. (2024)	Field, mesocosm	Pelagic, zooplankton community	$NaHCO_3+Na_2CO_3$	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	$NaHCO_3$, Na_2CO_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	$HCO_3^- + CO_3^{2-}$	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	$MgCl_2 \cdot 6H_2O + Na_2SiO_3 \cdot 5H_2O$	Fertilisation of diatom community due to nutrient release (DSi).
Flipkens et al. (2023)	Laboratory	Benthic, amphipod (*Gammarus locusta*)	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 (*Clupea harengus, Gadus morhua*)	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 (*Prochlorococcus*) 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 (*Prochlorococcus, Synechococcus,* 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 (*Nitzschia, Ditylum, Emiliana, Trichodesmium, Crocosphaera, Synechococcus*)	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 (*Leptocheirus plumulosus, Eohaustorius estuarius*), polychaete (*Neanthes arenaceodentata, Alitta virens*), bivalve (*Macoma nasuta*)	Olivine	No effect on survival and growth rates due to trace metal accumulation (Ni).
(Li et al. 2024)	Laboratory	Pelagic, phytoplankton (*Gephyrocapsa oceanica, Thalassiosira, pseudonana, Phaeodactylum tricornutum*)	Olivine	Positive effect on growth for highly silicified diatoms (*T. pseudonana*) 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

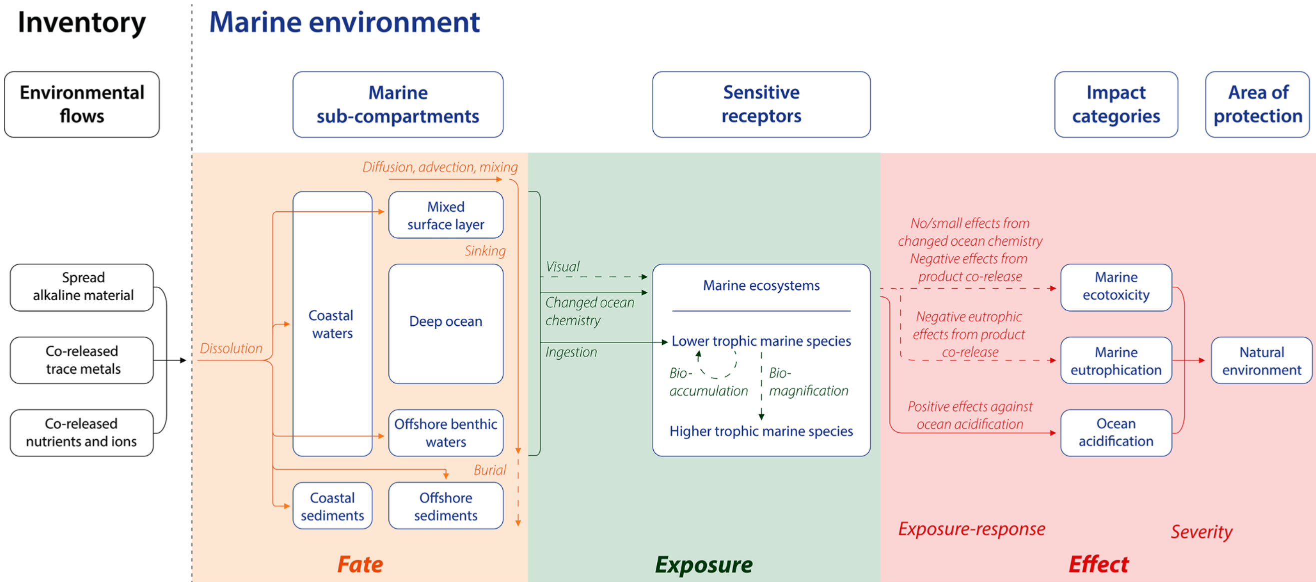

Fig. 3 Marine environmental impact pathways of ocean alkalinity enhancement (OAE). Solid arrows indicate established linkages, while dashed arrows represent uncertain or currently under-researched connections based on the present state of knowledge. (Note that a visual exposure process has been proposed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

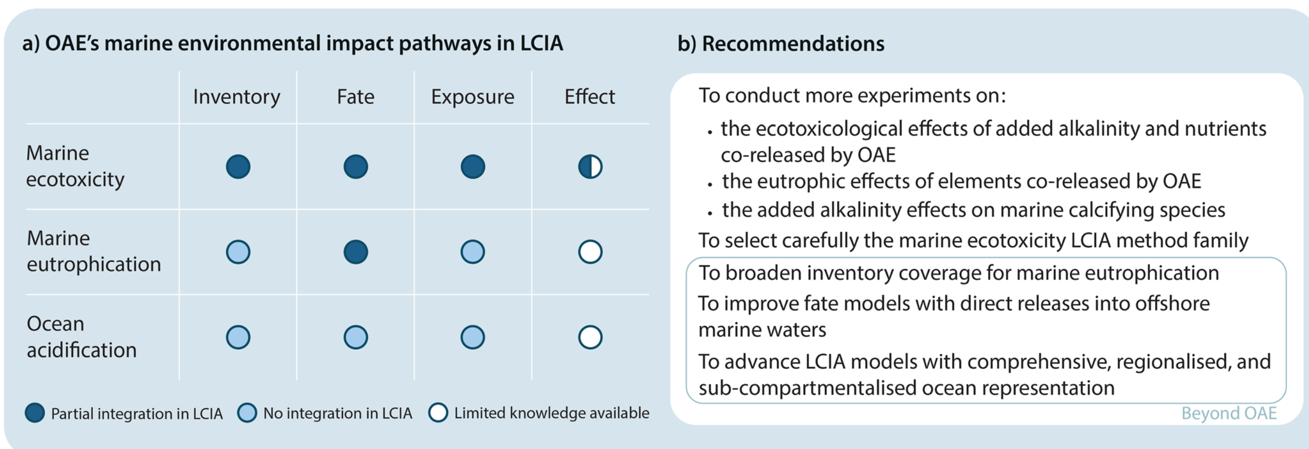

Fig. 4 Guidance for better integrating ocean alkalinity enhancement (OAE)'s marine environmental impacts in life cycle impact assessment (LCIA) models. (**a**) Summary of current integration of OAE's marine environmental impact pathways in LCIA models. Inventory refers to the elementary flows in the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

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 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 CO_2, 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 in ecoinvent, 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 CO_2, carbon monoxide (CO), and methane (CH_4)), 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 CO_2, 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; Vea 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 LCA

The methodological approach developed in this work enables the identification of marine environmental impact pathways of OAE, which requires combining the LCA 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 LCA. 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 LCA. 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 LCA 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 LCA 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 LCA. The primary function of OAE, like other mCDR technologies, is to remove atmospheric CO_2, and understanding how LCA 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 LCA 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 LCA (Levasseur et al. 2010) and remains an active discussion in the LCA 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.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11367-026-02707-z.

Acknowledgements Mona H. Delval, Patrik J.G. Henriksson, Pablo Trucco-Pignata, Patricia Grasse, Phil Renforth, and Nils Thonemann received funding from the European Union's Horizon Europe research and innovation programme (grant agreement n°101081362-2). Patrik J.G. Henriksson is partially funded by FORMAS CAPS (2023-01805) and Inequality and the Biosphere Projects (2020-00454), the European Union's Horizon Europe research and innovation programme (grant agreement no. 101182025). Paul Behrens was supported by a British Academy Global Professorship. Phil Renforth is supported by the Carbon to Sea Initiative. The authors would like to thank Louison F.J. Jacoby for his help on the visualisation and Jeroen B. Guinée for interesting discussions on LCIA development.

Author contributions Conceptualisation: M.H.D., P.J.G.H., P.B., N.T.; Methodology: M.H.D., P.J.G.H., P.B., L.S., N.T.; Investigation: M.H.D.; Validation: P.J.G.H., P.B., L.S., P.T.-P., P.G., P.R., N.T.; Visualisation: M.H.D.; Writing: - original draft: M.H.D.; Writing – review & editing: M.H.D., P.J.G.H., P.B., L.S., P.T.-P., P.G., P.R., N.T.

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.

References

Anandkumar A, Nagarajan R, Prabakaran K et al (2018) Human health risk assessment and bioaccumulation of trace metals in fish species collected from the miri coast. Mar Pollut Bull 133:655–663. https://doi.org/10.1016/j.marpolbul.2018.06.033

Anderson SR, Stadler K, Verones F (2025) From global emissions to local impacts: spatially explicit modeling of ocean acidification in life cycle assessment. Environ Sci Technol 59(42):22508–22517. https://doi.org/10.1021/acs.est.5c02069

Antoni D, Wichels A, Boersma M, Gerdts G (2025) The effect of ocean alkalinity enhancement on pelagic bacterial communities: focus points derived from a mesocosm experiment. Front Microbiomes 4:1606890. https://doi.org/10.3389/frmbi.2025.1606890

Azevedo LB, De Schryver AM, Hendriks AJ, Huijbregts MAJ (2015) Calcifying species sensitivity distributions for ocean acidification. Environ Sci Technol 49(3):1495–1500. https://doi.org/10.1021/es505485m

Bach LT, Gill SJ, Rickaby REM et al (2019) CO2 removal with enhanced weathering and ocean alkalinity enhancement: potential risks and co-benefits for marine pelagic ecosystems. Front Clim 1:7. https://doi.org/10.3389/fclim.2019.00007

Bednaršek N, Van De Mortel H, Pelletier G, García-Reyes M, Feely RA, Dickson AG (2025) Assessment framework to predict sensitivity of marine calcifiers to ocean alkalinity enhancement - identification of biological thresholds and importance of precautionary principle. Biogeosciences 22(2):473–498. https://doi.org/10.5194/bg-22-473-2025

Bhaumik A, Faucher G, Henning M et al (2025) Prey dynamics as a buffer: enhancing copepod resilience to ocean alkalinity enhancement. Environ Res Lett 20(2):024058. https://doi.org/10.1088/1748-9326/adaa8c

Britton D, Visch W, Bach LT (2025) Moderate ocean alkalinity enhancement likely to have minimal effects on a habitat-forming kelp across multiple life stages. Limnology Oceanogr 70(5):1283–1295. https://doi.org/10.1002/lno.70029

Browning TJ, Moore CM (2023) Global analysis of ocean phytoplankton nutrient limitation reveals high prevalence of co-limitation. Nat Commun 14(1):5014. https://doi.org/10.1038/s41467-023-40774-0

Camatti E, Valsecchi S, Caserini S et al (2024) Short-term impact assessment of ocean liming: a copepod exposure test. Mar Pollut Bull 198:115833. https://doi.org/10.1016/j.marpolbul.2023.115833

Campbell JS, Foteinis S, Furey V et al (2022) Geochemical negative emissions technologies: part I. review. Front Clim 4:879133. https://doi.org/10.3389/fclim.2022.879133

Carvalho BC, De Souza Junior HRA, Soares SR (2024) Evaluation of LCIA characterization models for marine ecotoxicity. The Int J Life Cycle Assess 29(4):706–732. https://doi.org/10.1007/s11367-023-02277-4

Caserini S, Storni N, Grosso M (2022) The availability of limestone and other raw materials for ocean alkalinity enhancement. Global Biogeochem Cycles 36(5):e2021GB007246. https://doi.org/10.1029/2021GB007246

Chahouri A, Elouahmani N, Ouchene H (2022) Recent progress in marine noise pollution: a thorough review. Chemosphere 291:132983. https://doi.org/10.1016/j.chemosphere.2021.132983

Cosme N, Hauschild MZ (2017) Characterization of waterborne nitrogen emissions for marine eutrophication modelling in life cycle impact assessment at the damage level and global scale. The Int J Life Cycle Assess 22(10):1558–1570. https://doi.org/10.1007/s11367-017-1271-5

Cosme N, Koski M, Hauschild MZ (2015) Exposure factors for marine eutrophication impacts assessment based on a mechanistic biological model. Ecol Modell 317:50–63. https://doi.org/10.1016/j.ecolmodel.2015.09.005

Cosme N, Mayorga E, Hauschild MZ (2018) Spatially explicit fate factors of waterborne nitrogen emissions at the global scale. The Int J Life Cycle Assess 23(6):1286–1296. https://doi.org/10.1007/s11367-017-1349-0

Dale AW, Geilert S, Diercks I et al (2024) Seafloor alkalinity enhancement as a carbon dioxide removal strategy in the Baltic Sea. Commun Earth Environ 5(1):452. https://doi.org/10.1038/s43247-024-01569-3

De Castro I, Ribeiro SC, Louvado A, Gomes NCM, Cachão M, Brito de Azevedo E, Barcelos e Ramos J (2025) Ocean liming effect on a North Atlantic microbial community: changes in composition and rates. Front Mar Sci 12:1602158. https://doi.org/10.3389/fmars.2025.1602158

De Pryck K, Boettcher M (2024) The rise, fall and rebirth of ocean carbon sequestration as a climate 'Solution'. Global Environ Change 85:102820. https://doi.org/10.1016/j.gloenvcha.2024.102820

Delacroix S, Nystuen TJ, Tobiesen AED, King AL, Höglund E (2024) Ocean alkalinity enhancement impacts: regrowth of marine microalgae in alkaline mineral concentrations simulating the initial concentrations after ship-based dispersions. Biogeosciences 21(16):3677–3690. https://doi.org/10.5194/bg-21-3677-2024

Delval MH, Thonemann N, Henriksson PJG et al (2025) Life cycle assessment of ocean-based carbon dioxide removal approaches: a systematic literature review. Renewable Sustain Energy Rev 224:116091. https://doi.org/10.1016/j.rser.2025.116091

Dong Y, Rosenbaum RK, Hauschild MZ (2016) Assessment of metal toxicity in marine ecosystems: comparative toxicity potentials for nine cationic metals in coastal seawater. Environ Sci Technol 50(1):269–278. https://doi.org/10.1021/acs.est.5b01625

Dong Y, Rosenbaum RK, Hauschild MZ (2018) Metal toxicity characterization factors for marine ecosystems—considering the importance of the estuary for freshwater emissions. The Int J Life Cycle Assess 23(8):1641–1653. https://doi.org/10.1007/s11367-017-1376-x

Dupont S, Metian M (2023) General considerations for experimental research on ocean alkalinity enhancement. State Planet 2-oae2023(2023):1–11. https://doi.org/10.5194/sp-2-oae2023-4-2023

EC-JRC (2012) Characterisation factors of the ILCD recommended life cycle impact assessment methods. Database and supporting information. European Commission, Joint Research Centre, Institute for Environment and Sustainability, Luxembourg

EC-JRC (2010) International Reference life cycle data System (ILCD) handbook. General Guide for life cycle assessment: detailed guidance. European Commission, Joint Research Centre, Institute for Environment and Sustainability, Luxembourg

Eisaman MD, Geilert S, Renforth P, Bastianini L, Campbell J, Dale AW, Foteinis S, Grasse P, Hawrot O, Löscher CR, Rau GH, Rønning J (2023) Assessing the technical aspects of ocean-alkalinity-enhancement approaches. State Planet 2-oae2023(2023):1–29. https://doi.org/10.5194/sp-2-oae2023-3-2023

Emanuelsson A, Ziegler F, Pihl L, Sköld M, Sonesson U (2014) Accounting for overfishing in life cycle assessment: new impact categories for biotic resource use. The Int J Life Cycle Assess 19(5):1156–1168. https://doi.org/10.1007/s11367-013-0684-z

Fantke P, Aurisano N, Bare J et al (2018) Toward harmonizing ecotoxicity characterization in life cycle impact assessment. Environ Toxicol Chem 37(12):2955–2971. https://doi.org/10.1002/etc.4261

Fauzi RT, Lavoie P, Sorelli L et al (2019) Exploring the current challenges and opportunities of life cycle sustainability assessment. Sustainability 11(3):636. https://doi.org/10.3390/su11030636

Ferderer A, Chase Z, Kennedy F et al (2022) Assessing the influence of ocean alkalinity enhancement on a coastal phytoplankton community. Biogeosciences 19(23):5375–5399. https://doi.org/10.5194/bg-19-5375-2022

Ferderer A, Schulz KG, Riebesell U et al (2024) Investigating the effect of silicate- and calcium-based ocean alkalinity enhancement on diatom silicification. Biogeosciences 21(11):2777–2794. https://doi.org/10.5194/bg-21-2777-2024

Flipkens G, Blust R, Town RM (2021) Deriving Nickel (Ni(ii)) and Chromium (Cr(iii)) based environmentally safe olivine guidelines for coastal enhanced silicate weathering. Environ Sci Technol 55(18):12362–12371. https://doi.org/10.1021/acs.est.1c02974

Flipkens G, Fuhr M, Fiers G et al (2023) Enhanced olivine dissolution in seawater through continuous grain collisions. Geochim Cosmochim Acta 359:84–99. https://doi.org/10.1016/j.gca.2023.09.002

Flipkens G, Horoba K, Bostyn K et al (2023) Acute bioaccumulation and chronic toxicity of olivine in the marine amphipod Gammarus locusta. Aquat Toxicol 262:106662. https://doi.org/10.1016/j.aquatox.2023.106662

Foteinis S, Andresen J, Campo F et al (2022) Life cycle assessment of ocean liming for carbon dioxide removal from the atmosphere. J Cleaner Prod 370:133309. https://doi.org/10.1016/j.jclepro.2022.133309

Foteinis S, Campbell JS, Renforth P (2023) Life cycle assessment of coastal enhanced weathering for carbon dioxide removal from air. Environ Sci Technol 57(15):6169–6178. https://doi.org/10.1021/acs.est.2c08633

Fuhr M, Dale AW, Wallmann K, Bährle R, Kalapurakkal HT, Sommer S, Spiegel T, Dobashi R, Buchholz B, Schmidt M, Perner M, Geilert S (2025) Calcite is an efficient and low-cost material to enhance benthic weathering in shelf sediments of the Baltic Sea. Commun Earth Environ 6(1):106. https://doi.org/10.1038/s43247-025-02079-6

Fuhr M, Wallmann K, Dale AW, Diercks I, Kalapurakkal HT, Schmidt M, Sommer S, Böhnke S, Perner M, Geilert S (2023) Disentangling artificial and natural benthic weathering in organic rich Baltic Sea sediments. Front Clim 5:1245580. https://doi.org/10.3389/fclim.2023.1245580

Gately JA, Kim SM, Jin B et al (2023) Coccolithophores and diatoms resilient to ocean alkalinity enhancement: A glimpse of hope? Sci Adv 9(24):eadg6066. https://doi.org/10.1126/sciadv.adg6066

Goldenberg SU, Riebesell U, Brüggemann D, Börner G, Sswat M, Folkvord A, Couret M, Spjelkavik S, Sánchez N, Jaspers C, Moyano M (2024) Early life stages of fish under ocean alkalinity enhancement in coastal plankton communities. Biogeosciences 21(20):4521–4532. https://doi.org/10.5194/bg-21-4521-2024

Gore S, Renforth P, Perkins R (2019) The potential environmental response to increasing ocean alkalinity for negative emissions. Mitig Adapt Strateg Glob Change 24(7):1191–1211. https://doi.org/10.1007/s11027-018-9830-z

Guo JA, Strzepek RF, Swadling KM et al (2024) Influence of ocean alkalinity enhancement with olivine or steel slag on a coastal plankton community in Tasmania. Biogeosciences 21(9):2335–2354. https://doi.org/10.5194/bg-21-2335-2024

Guo JA, Strzepek RF, Yuan Z et al (2025) Effects of ocean alkalinity enhancement on plankton in the equatorial Pacific. Commun Earth Environ 6(1):270. https://doi.org/10.1038/s43247-025-02248-7

Hajjar C, Bulle C, Agez M et al (2025) Identifying influencing physical and environmental parameters on fate and characterization factors for microplastic emissions in the marine environment. The Int J Life Cycle Assess 30(4):728–748. https://doi.org/10.1007/s11367-024-02421-8

Hajjar C, Bulle C, Boulay A-M (2024) Life cycle impact assessment framework for assessing physical effects on biota of marine microplastics emissions. The Int J Life Cycle Assess 29(1):25–45. https://doi.org/10.1007/s11367-023-02212-7

Halpern BS, Frazier M, Afflerbach J, Lowndes JS, Micheli F, O'Hara C, Scarborough C, Selkoe KA (2019) Recent pace of change in human impact on the world's ocean. Sci Rep 9(1):11609. https://doi.org/10.1038/s41598-019-47201-9

Hartmann J, Suitner N, Lim C, Schneider J, Marín-Samper L, Arístegui J, Renforth P, Taucher J, Riebesell U (2023) Stability of alkalinity in ocean alkalinity enhancement (OAE) approaches – consequences for durability of CO_2 storage. Biogeosciences 20(4):781–802. https://doi.org/10.5194/bg-20-781-2023

Harvey LDD (2008) Mitigating the atmospheric CO_2 increase and ocean acidification by adding limestone powder to upwelling regions. J Geophys Res 113(C4):C04028. https://doi.org/10.1029/2007JC004373

Hauschild MZ, Huijbregts MAJ (eds) (2015) Life cycle impact assessment. Springer, Netherlands, Dordrecht

He J, Tyka MD (2023) Limits and CO_2 equilibration of near-coast alkalinity enhancement. Biogeosciences 20(1):27–43. https://doi.org/10.5194/bg-20-27-2023

Henryson K, Hansson P-A, Sundberg C (2018) Spatially differentiated midpoint indicator for marine eutrophication of waterborne emissions in Sweden. The Int J Life Cycle Assess 23(1):70–81. https://doi.org/10.1007/s11367-017-1298-7

Huijbregts MAJ, Steinmann ZJN, Elshout PMF et al (2017) ReCiPe 2016 v1.1: a harmonized life cycle impact assessment method at midpoint and endpoint level Report I: characterization. RIVM, Netherlands

Huijbregts MAJ, Thissen U, Guinee JB et al (2000) Priority assessment of toxic substances in life cycle assessment. Part I: calculation of toxicity potentials for 181 substances with the nested multi-media fate, exposure and effects model USES–LCA. Chemosphere 41(4):541–573. https://doi.org/10.1016/S0045-6535(00)00030-8

Hutchins DA, Fu F-X, Yang S-C et al (2023) Responses of globally important phytoplankton species to olivine dissolution products and implications for carbon dioxide removal via ocean alkalinity enhancement. Biogeosciences 20(22):4669–4682. https://doi.org/10.5194/bg-20-4669-2023

IPCC (2023) IPCC, 2023. In: Climate change, 2023: synthesis Report. Contribution of working groups I, II and III to the sixth assessment Report of the intergovernmental panel on climate change [core Writing team, H Lee and J Romero (eds)]. IPCC, Geneva, Switzerland, pp 35–115

Isometric (2025) 625.64 credits issued to planetary. https://registry.isometric.com/issuance/iss_1JXW6N77B1S05B02. 7 July 2025

Jankowska E, Montserrat F, Romaniello SJ et al (2024) Metal bioaccumulation and effects of olivine sand exposure on benthic marine invertebrates. Chemosphere 358:142195. https://doi.org/10.1016/j.chemosphere.2024.142195

Jones K, Hemery LG, Ward ND et al (2025) Biological response of eelgrass epifauna, Taylor's Sea hare (*Phyllaplysia taylori*) and eelgrass isopod (*Idotea resecata*), to elevated ocean alkalinity. Biogeosciences 22(6):1615–1630. https://doi.org/10.5194/bg-22-1615-2025

Jouffray J-B, Blasiak R, Norström AV, Österblom H, Nyström M (2020) The blue acceleration: the trajectory of human expansion into the ocean. One Earth 2(1):43–54. https://doi.org/10.1016/j.oneear.2019.12.016

Katish M, Millar R, Foteinis S, Renforth P (2026) Life cycle assessment of ocean alkalinity enhancement using hydrated carbonate minerals. Environ Technol Innovation 41:104849. https://doi.org/10.1016/j.eti.2026.104849

Kounina A, Margni M, Shaked S et al (2014) Spatial analysis of toxic emissions in LCA: a sub-continental nested USEtox model with freshwater archetypes. Environ Int 69:67–89. https://doi.org/10.1016/j.envint.2014.04.004

Kousoulas K, Ferderer A, Eriksen R, Bach LT (2025) Winners and losers under hydroxide-based ocean alkalinity enhancement in a Tasmanian plankton community. J Phycol 61(4):989–1006. https://doi.org/10.1111/jpy.70052

Kowalczyk KA, Amann T, Strefler J et al (2024) Marine carbon dioxide removal by alkalinization should no longer be overlooked. Environ Res Lett 19(7):074033. https://doi.org/10.1088/1748-9326/ad5192

Kwong RWM (2024) Trace metals in the teleost fish gill: biological roles, uptake regulation, and detoxification mechanisms. J Comp Physiol B 194(5):749–763. https://doi.org/10.1007/s00360-024-01565-1

Levasseur A, Lesage P, Margni M, Deschênes L, Samson R (2010) Considering time in LCA: dynamic LCA and its application to global warming impact assessments. Environ Sci Technol 44(8):3169–3174. https://doi.org/10.1021/es9030003

Li C, Liu X, Li Y et al (2024) The interactions between olivine dissolution and phytoplankton in seawater: potential implications for ocean alkalinization. Sci Total Environ 912:168571. https://doi.org/10.1016/j.scitotenv.2023.168571

Lindland M, Wigand EA, Fagerholt K et al (2025) Supply chain optimization for ocean alkalinity enhancement: a Norwegian case study. Int J Greenhouse Gas Control 145:104395. https://doi.org/10.1016/j.ijggc.2025.104395

Liu F, Daewel U, Kossack J et al (2025) Evaluating ocean alkalinity enhancement as a carbon dioxide removal strategy in the North Sea. Biogeosciences 22(14):3699–3719. https://doi.org/10.5194/bg-22-3699-2025

Liu H, Song Y, Zhang X et al (2021) Spatial variation in primary production in the Eastern Indian ocean. Front Mar Sci 8:757529. https://doi.org/10.3389/fmars.2021.757529

Marín-Samper L, Arístegui J, Hernández-Hernández N et al (2024) Assessing the impact of CO_2 -equilibrated ocean alkalinity enhancement on microbial metabolic rates in an oligotrophic system. Biogeosciences 21(11):2859–2876. https://doi.org/10.5194/bg-21-2859-2024

Mayes WM, Younger PL, Aumônier J (2008) Hydrogeochemistry of alkaline steel slag leachates in the UK. Water Air Soil Pollut 195(1–4):35–50. https://doi.org/10.1007/s11270-008-9725-9

Mendes I, Lübbers J, Schönfeld J, Baldermann A, Carrasco AR, Cravo A, Gomes A, Grasse P, Stamm FM (2025) Novel field experiment on alkalinity enhancement in intertidal environments-A trailblazer for natural climate solutions. JGR Biogeosci 130(3):e2024JG008591. https://doi.org/10.1029/2024JG008591

Meysman FJR, Montserrat F (2017) Negative CO_2 emissions via enhanced silicate weathering in coastal environments. Biol Lett 13(4):20160905. https://doi.org/10.1098/rsbl.2016.0905

Montserrat F, Renforth P, Hartmann J et al (2017) Olivine dissolution in seawater: implications for CO_2 sequestration through enhanced weathering in coastal environments. Environ Sci Technol 51(7):3960–3972. https://doi.org/10.1021/acs.est.6b05942

Moras CA, Bach LT, Cyronak T et al (2022) Ocean alkalinity enhancement – avoiding runaway $CaCO_3$ precipitation during quick and hydrated lime dissolution. Biogeosciences 19(15):3537–3557. https://doi.org/10.5194/bg-19-3537-2022

Moras CA, Joannes-Boyau R, Bach LT et al (2024) Carbon dioxide removal efficiency of iron and steel slag in seawater via ocean alkalinity enhancement. Front Clim 6:1396487. https://doi.org/10.3389/fclim.2024.1396487

Myridinas M, Fennel K, Laurent A et al (2026) Prospective site-specific life cycle assessment of ocean alkalinity enhancement. Environ Res Lett 21(8):084010. https://doi.org/10.1088/1748-9326/ae5a4e

NASEM (2022) A research strategy for ocean-based carbon dioxide removal and sequestration, National Academies of Sciences, engineering, and medicine. National Academies Press, Washington D.C

Ninove F, Le Traon P-Y, Remy E, Guinehut S (2016) Spatial scales of temperature and salinity variability estimated from Argo observations. Ocean Sci 12(1):1–7. https://doi.org/10.5194/os-12-1-2016

Nocera AC, Traboni C, Courboulès J et al (2025) The effect of ocean alkalinity enhancement on zooplankton standing stock and community composition in the Eastern Mediterranean Sea: a mesocosm study. Mar Environ Res 212:107489. https://doi.org/10.1016/j.marenvres.2025.107489

Oberlander JL, Burke ME, London CA, MacIntyre HL (2025) Assessing the impacts of simulated ocean alkalinity enhancement on viability and growth of nearshore species of phytoplankton. Biogeosciences 22(2):499–512. https://doi.org/10.5194/bg-22-499-2025

Oberschelp C, Pfister S, Hellweg S (2020) Globally regionalized monthly life cycle impact assessment of particulate matter. Environ Sci Technol 54(24):16028–16038. https://doi.org/10.1021/acs.est.0c05691

Ocean Visions (2022) Ocean-based carbon dioxide removal. https://oceanvisions.org/ocean-based-carbon-dioxide-removal/. 15 May 2024

Orr JC, Fabry VJ, Aumont O et al (2005) Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. Nature 437(7059):681–686. https://doi.org/10.1038/nature04095

Oschlies A, Bach LT, Fennel K et al (2025) Perspectives and challenges of marine carbon dioxide removal. Front Clim 6:1506181. https://doi.org/10.3389/fclim.2024.1506181

Paul AJ, Haunost M, Goldenberg SU, Hartmann J, Sánchez N, Schneider J, Suitner N, Riebesell U (2025) Ocean alkalinity enhancement in an open-ocean ecosystem: biogeochemical responses and carbon storage durability. Biogeosciences 22(12):2749–2766. https://doi.org/10.5194/bg-22-2749-2025

Piacenza SE, Barner AK, Benkwitt CE, Boersma KS, Cerny-Chipman EB, Ingeman KE, Kindinger TL, Lee JD, Lindsley AJ, Reimer JN, Rowe JC, Shen C, Thompson KA, Thurman LL, Heppell SS (2015) Patterns and variation in benthic biodiversity in a large marine ecosystem. PLoS ONE 10(8):e0135135. https://doi.org/10.1371/journal.pone.0135135

Ramírez L, Pozzo-Pirotta LJ, Trebec A, Manzanares-Vázquez V, Díez JL, Arístegui J, Riebesell U, Archer SD, Segovia M (2025) Ocean alkalinity enhancement (OAE) does not cause cellular stress in a phytoplankton community of the subtropical Atlantic ocean. Biogeosciences 22(7):1865–1886. https://doi.org/10.5194/bg-22-1865-2025

Rastelli E, Corinaldesi C, Dell'anno A, Amaro T, Greco S, Lo Martire M, Carugati L, Queirós AM, Widdicombe S, Danovaro R (2016) CO_2 leakage from carbon dioxide capture and storage (CCS) systems affects organic matter cycling in surface marine sediments. Mar Environ Res 122:158–168. https://doi.org/10.1016/j.marenvres.2016.10.007

Ren H, Hu Y, Zhang L et al (2025) Olivine-induced seasonal dynamics of eukaryotic microalgal and bacterial assemblages in

mid-latitude nearshore marine ecosystems. Mar Pollut Bull 216:117964. https://doi.org/10.1016/j.marpolbul.2025.117964
Renforth P, Baltruschat S, Peterson K et al (2022) Using ikaite and other hydrated carbonate minerals to increase ocean alkalinity for carbon dioxide removal and environmental remediation. Joule 6(12):2674–2679. https://doi.org/10.1016/j.joule.2022.11.001
Renforth P, Henderson G (2017) Assessing ocean alkalinity for carbon sequestration. Rev Geophysics 55(3):636–674. https://doi.org/10.1002/2016RG000533
Richter S, Scherer L, Hegwood M et al (2024) Conceptual framework for considering animal welfare in sustainability assessments of foods. Sustain Prod Consumption 52:179–209. https://doi.org/10.1016/j.spc.2024.10.004
Ringham MC, Hirtle N, Shaw C et al (2024) An assessment of ocean alkalinity enhancement using aqueous hydroxides: kinetics, efficiency, and precipitation thresholds. Biogeosciences 21(15):3551–3570. https://doi.org/10.5194/bg-21-3551-2024
Rosenbaum RK, Bachmann TM, Gold LS et al (2008) Usetox—the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. The Int J Life Cycle Assess 13(7):532–546. https://doi.org/10.1007/s11367-008-0038-4
Sánchez N, Goldenberg SU, Brüggemann D et al (2024) Plankton food web structure and productivity under ocean alkalinity enhancement. Sci Adv 10(49):eado0264. https://doi.org/10.1126/sciadv.ado0264
Scherer L, Gürdal İ, Van Bodegom PM (2022) Characterization factors for ocean acidification impacts on marine biodiversity. J Ind Ecol 26(6):2069–2079. https://doi.org/10.1111/jiec.13274
Sherman K, Donnelly K (2026) Advancing towards large marine ecosystem sustainability. Environ Dev 57:101356. https://doi.org/10.1016/j.envdev.2025.101356
Smith S, Geden O, Gidden M et al (2024) The state of carbon dioxide removal 2nd edn
Stoessel F, Sonderegger T, Bayer P, Hellweg S (2018) Assessing the environmental impacts of soil compaction in life cycle assessment. Sci Total Environ 630:913–921. https://doi.org/10.1016/j.scitotenv.2018.02.222
Struijs J, Beusen A, van Jaarsveld H, Huijbregts M (2009) Chapter, 6: aquatic eutrophication. in: ReCiPe 2008 - a life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level, First edn. Netherlands, pp 59–67
Subhas AV, Marx L, Reynolds S et al (2022) Microbial ecosystem responses to alkalinity enhancement in the North Atlantic subtropical gyre. Front Clim 4:784997. https://doi.org/10.3389/fclim.2022.784997
Traboni C, Nocera AC, Romano F, Courboulès J, Chantzaras C, Magiopoulos I, Varliero S, Basso D, Pitta P (2025) Plankton do not care: minimal effects of ocean liming on plankton growth and grazing in the Eastern Mediterranean. Limnology Oceanogr 70(S2):1–16. https://doi.org/10.1002/lno.70136
Van Zelm R, Huijbregts MAJ, Van De Meent D (2009) USES-LCA 2.0—a global nested multi-media fate, exposure, and effects model. The Int J Life Cycle Assess 14(3):282–284. https://doi.org/10.1007/s11367-009-0066-8
Vea EB, Jwaideh M, Richardson K, Ryberg M, Bjørn A, Hauschild M (2024) Enabling comprehensive assessment of marine eutrophication impacts and their evaluation against regional safe operating space. The Int J Life Cycle Assess 29(9):1738–1755. https://doi.org/10.1007/s11367-024-02311-z
Verones F, Hellweg S, Antón A, Azevedo LB, Chaudhary A, Cosme N, Cucurachi S, de Baan L, Dong Y, Fantke P, Golsteijn L, Hauschild M, Heijungs R, Jolliet O, Juraske R, Larsen H, Laurent A, Mutel CL, Margni M, Núñez M, Owsianiak M, Pfister S, Ponsioen T, Preiss P, Rosenbaum RK, Roy P-O, Sala S, Steinmann Z, van Zelm R, Van Dingenen R, Vieira M, Huijbregts MAJ (2020) LC-IMPACT: a regionalized life cycle damage assessment method. J Ind Ecol 24(6):1201–1219. https://doi.org/10.1111/jiec.13018
Woods JS, Veltman K, Huijbregts MAJ et al (2016) Towards a meaningful assessment of marine ecological impacts in life cycle assessment (LCA). Environ Int 89-90:48–61. https://doi.org/10.1016/j.envint.2015.12.033
Woods JS, Verones F, Jolliet O, Vázquez-Rowe I, Boulay A-M (2021) A framework for the assessment of marine litter impacts in life cycle impact assessment. Ecol Indic 129:107918. https://doi.org/10.1016/j.ecolind.2021.107918
Xin X, Goldenberg SU, Taucher J, Stuhr A, Arístegui J, Riebesell U (2024) Resilience of phytoplankton and microzooplankton communities under ocean alkalinity enhancement in the oligotrophic ocean. Environ Sci Technol 58(47):20918–20930. https://doi.org/10.1021/acs.est.4c09838
Yang B, Leonard J, Langdon C (2023) Seawater alkalinity enhancement with magnesium hydroxide and its implication for carbon dioxide removal. Mar Chem 253:104251. https://doi.org/10.1016/j.marchem.2023.104251
Yang C, Feng EY (2026) Life cycle perspective-based modeling assessment of ocean alkalinity enhancement. Environ Sci Technol 60(5):4008–4019. https://doi.org/10.1021/acs.est.5c13054
Zhuang W, Zhu T, Li F et al (2025) Potential environmental impacts and management strategies for metal release during ocean alkalinity enhancement using olivine. Environ Sci Technol 59(2):1091–1099. https://doi.org/10.1021/acs.est.4c10705

Authors and Affiliations

Mona H. Delval[1] · **Patrik J. G. Henriksson**[1,2] · **Paul Behrens**[1,3] · **Laura Scherer**[1] · **Pablo Trucco-Pignata**[4] · **Patricia Grasse**[5,6] · **Phil Renforth**[7] · **Nils Thonemann**[1]

✉ Mona H. Delval
m.h.delval@cml.leidenuniv.nl

1 Institute of Environmental Sciences (CML), Leiden University, Einsteinweg 2, Leiden 2333 CC, The Netherlands

2 Stockholm Resilience Centre, Stockholm University, Albanovägen 28, Stockholm 106 91, Sweden

3 Oxford Martin School, University of Oxford, 34 Broad St, Oxford OX1 3BD, UK

4 National Oceanography Centre, Southampton, UK

5 German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, 04103 Leipzig, Germany

6 GEOMAR Helmholtz Centre for Ocean Research Kiel, 24148 Kiel, Germany

7 Research Centre for Carbon Solutions, Heriot-Watt University, Edinburgh, UK