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Life cycle assessment of ocean-based carbon dioxide removal approaches: A systematic literature review

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ABSTRACT

As climate impacts worsen, novel technologies to draw down atmospheric carbon are gaining attention. One such approach is ocean-based carbon dioxide removal (OCDR). However, the potential environmental side-effects of large-scale OCDR deployment remain understudied. Here, we present a systematic literature review of the life cycle assessments (LCAs) of OCDR approaches. We find that current OCDR LCAs have a limited scope, often overlook environmental impacts beyond global warming, and that LCA as a method is currently limited in capturing aquatic impacts. We provide several recommendations for future work, such as using a functional unit of storing atmospheric carbon over a specified time horizon and in a specified medium, performing cradle-to-grave analysis, including more (marine) environmental impacts, and estimating uncertainties. We also emphasise the need to develop the LCA methodology further for better assessing marine environment impacts.

1. Introduction

Greenhouse gas (GHG) emissions released by human activities are causing catastrophic damage to the Earth's ecosystems and human society. This damage is expected to worsen with further global warming [1]. The Paris Agreement established a global goal to "pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels" [2], necessitating a significant reduction in emissions in the coming years and worldwide carbon neutrality by 2100 [1,3]. Many of the possible trajectories towards carbon neutrality reported in IPCC reports rely heavily on the rapid large-scale deployment of carbon dioxide removal (CDR) approaches, also called negative emission technologies (NETs), to reduce net emissions and offset residual emissions [1,4].

Land-based CDR (LCDR) has seen increasing interest from the scientific community [4]. However, given that the ocean is the largest carbon sink on the planet, storing 16 times more carbon than the terrestrial biosphere and 50 times more than the atmosphere, there is a potential for large-scale deployment of ocean-based CDR (OCDR), also referred to as marine CDR (mCDR) [6,7]. The ocean covers 70 % of the Earth's surface and has already absorbed more than a quarter of anthropogenic CO_2 emissions via physical and chemical processes since the beginning of the industrial era [8–10]. However, enhancing ocean carbon sinks comes with potential environmental trade-offs. For example, CDR through ocean fertilisation could alter species composition and oxygen levels and increase acidification in deep waters [11,12], impacting marine ecosystems. OCDR approaches could add additional environmental pressures on the ocean, which already faces other anthropogenic pressures, such as fishing.

There are many open questions as to what extent OCDR can be used and the environmental trade-offs these approaches might involve, especially when considering large-scale deployment. Life cycle assessment (LCA) is commonly used to assess the environmental performance of a product or service along its entire life cycle [13]. For new technologies, such as OCDR, a prospective LCA is one tool to explore future environmental performance to anticipate avoidable impacts and mitigate them [14–16].

There are several reviews on LCAs of CDR approaches and efforts to identify LCA improvements across these reviews [17–22]. They generally call for increased transparency [20,21], the use of a functional unit (FU) appropriate for carbon removal [17,20,21], such as per tonne of CO_2 removed [20,21], to assess impacts of CDR approaches beyond

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List of abbreviations

GHG	Greenhouse gas
CDR	Carbon dioxide removal
NET	Negative emission technology
LCDR	Land-based carbon dioxide removal
OCDR	Ocean-based carbon dioxide removal
mCDR	Marine carbon dioxide removal
LCA	Life cycle assessment
FU	Functional unit
CO_2	Carbon dioxide
DACCS	Direct air carbon dioxide capture and storage
BECCS	Bioenergy carbon capture and storage
OAE	Ocean alkalinity enhancement
mBECCS	Marine bioenergy production coupled with carbon capture and storage
CCS	Carbon capture storage
CCU	Carbon capture utilisation
CCUS:	Carbon capture storage and utilisation
Blue CDR	Blue carbon dioxide removal
Electrochemical OCDR	Electrochemical ocean-based carbon dioxide removal
DIC	Dissolved inorganic carbon
CH_4	Methane
LCC	Life cycle costing
MC	Monte Carlo
CF	Characterisation factor
LCIA	Life cycle impact assessment
DAC	Direct air capture
ABECCS	Aquatic bioenergy carbon capture and storage
IAM	Integrated assessment model
SSP	Shared socioeconomic pathway
OAT	One-at-a-time
TRL:	Technical readiness level

simply climate outcomes [17,20,22], to solve multifunctionality using allocation rather than substitution to prevent avoided emissions to be considered as negative and thus bias results [20,21], and to account for the temporality of GHG emissions and removals [17,20,21]. However, these reviews mostly assess land-based CDR and only have a limited inclusion of OCDR, if any.

A review of the current state of knowledge on the environmental performance of OCDR approaches and their potential is currently lacking. As OCDR operates in very different environments than LCDR, they may require different or additional considerations when performing an LCA. Such a review is important given current research and policy arguments for a portfolio of diverse CDR approaches, both on land and offshore [4,6]. To fill this knowledge gap, we assess the current state of knowledge and practices of LCAs on OCDR approaches via a systematic literature review following PRISMA reporting guidelines [23]. We aim to identify knowledge gaps and uncertainties regarding the environmental assessment of OCDR approaches. Based on our results, we provide recommendations to guide future OCDR LCAs.

2. Method

As the definition of CDR varies across the literature, we used the IPCC definition: "*Anthropogenic activities removing carbon dioxide (CO_2) from the atmosphere and durably storing it in geological, terrestrial or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhance of biological or geochemical CO_2 sinks and direct air carbon dioxide capture and storage (DACCS) but exclude natural CO_2 uptake not directly caused by human activities*" [5]. This definition also follows the recommendations from Smith et al. [4], who summarise the latest CDR findings.

OCDR approaches are commonly defined as approaches that enhance the capacity of oceans to sequester carbon [6]. This implies that OCDR approaches have oceans as the destination for durable carbon storage. However, some OCDR approaches in the literature extend this definition by capturing carbon in oceans but storing it durably elsewhere (e.g., macroalgae cultivated offshore for bioenergy carbon capture and storage (BECCS)) or by using marine biomass to provide a CDR service on land (e.g., marine biomass for biochar production) [7,24,25]. Hence, we defined OCDR approaches as CDR approaches deployed (entirely or only for some stages of the technology) in the marine environment and/or using marine biomass to provide a CDR service.

We identify the following ten categories of OCDR in the literature [6,7,24,25]: macroalgae cultivation and sinking; ocean fertilisation; blue CDR; ocean alkalinity enhancement (OAE); CDR with deep-sea storage; marine bioenergy production coupled with carbon capture and storage (mBECCS), biochar from marine biomass; electrochemical OCDR, artificial upwelling and downwelling; and terrestrial biomass sinking (Fig. 1). For complete definitions, see Table 1 and for a schematic of how they operate, see Fig. 2. Carbon capture storage and/or utilisation (CCS, CCU, and CCUS) technologies, as well as approaches storing CO_2 captured from non-atmospheric sources, such as those from industrial activities (e.g., from fossil fuel burning in power plants or from cement production), did not match the definition of CDR and we exclude them.

We searched for scientific articles that conducted an LCA of OCDR approach(es) on Scopus and Web of Science databases. We used general search terms related to OCDR approaches (e.g., "ocean-based carbon dioxide removal" or "marine carbon dioxide removal") and combined these terms with terms related to LCA (e.g., "life cycle assessment" or "life cycle analysis"). We then combined terms related to each specific OCDR approach (e.g., "ocean fertili*" or "ocean-based fertili*") with search terms related to LCA (see SI for a complete list of search terms).

We conducted the literature search from December 2023 to June 2024 with no limitation on publication date (see the SI for exclusion criteria and more information on our literature screening process per OCDR approach). We also included one LCA case study, suggested by a reviewer, as it aligned with our inclusion criteria. We structured the review by each approach. We first reviewed the essential elements of the LCA methodology used in each study we identified, including system boundaries, the FU, multifunctionality, and the environmental impact categories (in a similar structure to Terlouw et al. [20]). For the impact categories, we identified the inclusion of categories concerning the marine environment. We also reviewed the study goal, LCA approach (consequential or attributional), foreground data sources, LCI database (s), and LCA software used. As large uncertainties surround emerging approaches like OCDR and LCA methodologies, we also specifically evaluate uncertainty considerations across the LCAs (including data uncertainty and model uncertainty [30]).

3. Results

In total, we found 20 LCAs on OCDR approaches (Fig. 3). We found that the largest number of LCAs studies blue CDR ($n = 6$) and only assesses coastal ecosystems. CDR with deep-sea storage, for which carbon is injected into the deep sea or under the seabed into saline aquifers, has reasonable coverage in LCAs ($n = 17$), but the focus is mainly on storing CO_2 emitted by industrial activities rather than atmospheric CO_2. Fewer studies evaluate CO_2 deep-sea storage from atmospheric sources ($n = 3$). We also found a large body of LCA literature on marine biomass for biochar production ($n = 13$). To qualify as an OCDR approach, marine biomass needs to be grown from dissolved atmospheric CO_2. However,

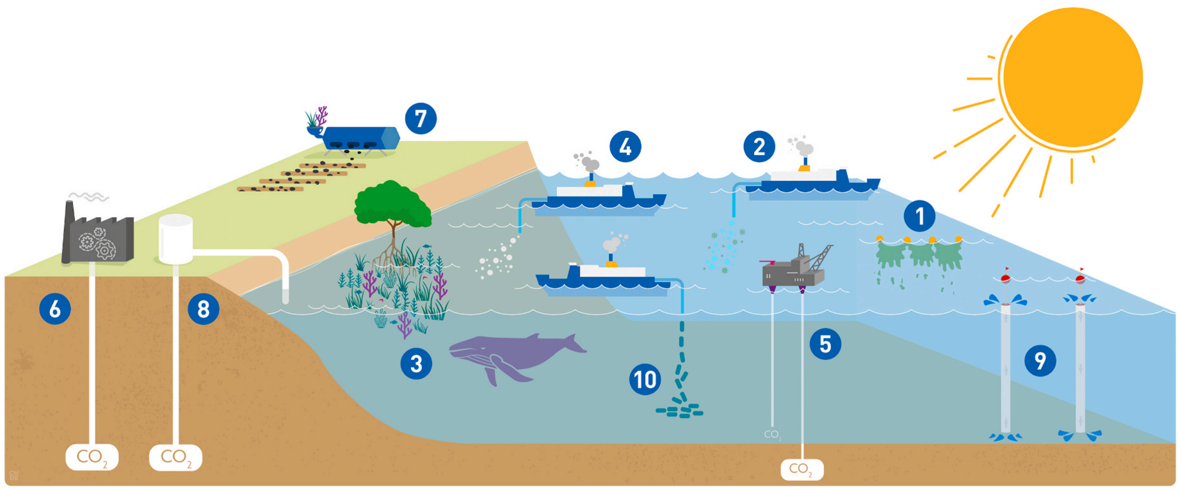

Fig. 1. The different OCDR approaches assessed in this review, namely: (1) Macroalgae cultivation and sinking (Section 3.1); (2) Ocean fertilisation (Section 3.2); (3) Blue CDR (Section 3.3); (4) OAE (Section 3.4); (5) CDR with deep-sea storage (Section 3.5); (6) mBECCS (Section 3.6); (7) Marine biomass for biochar production (Section 3.7); (8) Electrochemical OCDR (Section 3.8.1); (9) Artificial upwelling and downwelling (Section 3.8.2); and (10) Terrestrial biomass sinking (Section 3.8.3). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Summary of key terms used in this paper with their abbreviations and definitions.

Term	Definition
Macroalgae cultivation and sinking	Cultivation of macroalgae for carbon capture through photosynthesis with the subsequent sinking of seaweed biomass for carbon storage in the deep ocean [6,7].
Ocean fertilisation	Addition of micronutrients and/or macronutrients to the ocean surface to promote carbon capture and storage through the biological carbon pump [6].
Blue carbon dioxide removal (blue CDR)	Human-induced enhancement of the natural carbon sequestration potential of marine and coastal ecosystems, excluding the protection and conservation of current ecosystems [26].
Ocean alkalinity enhancement (OAE)	Addition of alkaline substances to the ocean surface to promote the formation of stable forms of carbon, providing durable storage [6,7]. Also termed ocean alkalinisation, ocean-enhanced weathering, or ocean liming.
CDR with deep-sea storage	Durable storage of atmospheric CO_2 in the deep ocean or below the seabed [7].
Marine biomass for bioenergy production with carbon capture and storage (mBECCS)	Production of bioenergy from marine biomass (e.g., algae) coupled with durable carbon storage [7]. Also termed aquatic BECCS (ABECCS).
Biochar from marine biomass	Production of biochar from marine biomass (e.g., algae) and application as soil amendment for durable carbon storage [7,27–29].
Electrochemical ocean-based carbon dioxide removal (electrochemical OCDR)	Seawater electrolysis to promote carbon removal or ocean's capacity for carbon sequestration [6,7]. Also termed electrochemical direct ocean capture [7].
Artificial upwelling and downwelling	Pumping up deep ocean waters to promote carbon capture and storage through the biological carbon pump and pumping down surface ocean waters to enhance carbon storage in the deep ocean [6,7].
Terrestrial biomass sinking	Sinking of terrestrial biomass (e.g., agriculture residues) and its photosynthetically captured carbon to the deep sea for carbon storage [7].

most technologies studied involve microalgae cultivation using CO_2 from flue gas or wastewater ($n = 6$). A similar observation was made by Even et al. [31] related to microalgae for mBECCS, with traditional microalgae cultivation typically using CO_2 from industrial source.

We present the results of the systematic literature review per OCDR approach. For each OCDR approach, we give a general technology description from the literature. See the SI for a complete technology description of the OCDR approaches assessed in the LCAs reviewed and additional results on LCA practice for OCDR approaches.

3.1. *Macroalgae cultivation and sinking*

3.1.1. *General description*

This CDR involves macroalgae cultivation, harvest, and subsequent intentional or natural sinking to the deep ocean, where a fraction of biomass is then presumed to be durably sequestered [6]. Macroalgae capture dissolved inorganic carbon (DIC) during photosynthesis. This causes a seawater deficiency in DIC, allowing more carbon to be drawn out of the atmosphere and into the ocean waters to re-equilibrate. The net result is a reduction in atmospheric CO_2 [32].

3.1.2. *LCA*

We found two LCA studies on macroalgae sinking that matched our inclusion criteria: Coleman et al. [32] and N'Yeurt et al. [33].

Study goal. Both studies conduct LCAs alongside economic assessments. Coleman et al. [32] assess CO_2-eq. emitted by the macroalgae cultivation and sinking system and compare it with the overall quantity of CO_2 sequestered to estimate net sequestration. N'Yeurt et al. [33] investigate the efficiency of their macroalgae system both in terms of carbon removal and net energy production. Coleman et al. [32] specify that the system is deployed in the United States (US) whereas N'Yeurt et al. [33] do not specify the geographic scope.

System boundaries. Both studies assess similar life-cycle stages, including macroalgae cultivation, harvest, and intentional biomass sinking. However, Coleman et al. [32] separate cultivation between an earlier growth stage on land and a later stage offshore, including a transport stage of the harvested biomass to the sinking site. N'Yeurt et al. [33] include other stages, namely digestion of the harvested microalgae, recovery of methane (CH_4) for energy production, and recycling of macroalgae nutrients within the system. Both LCA studies adopt a cradle-to-grave approach, although Coleman et al. [32] do not include the carbon absorbed by the macroalgae during cultivation but calculate

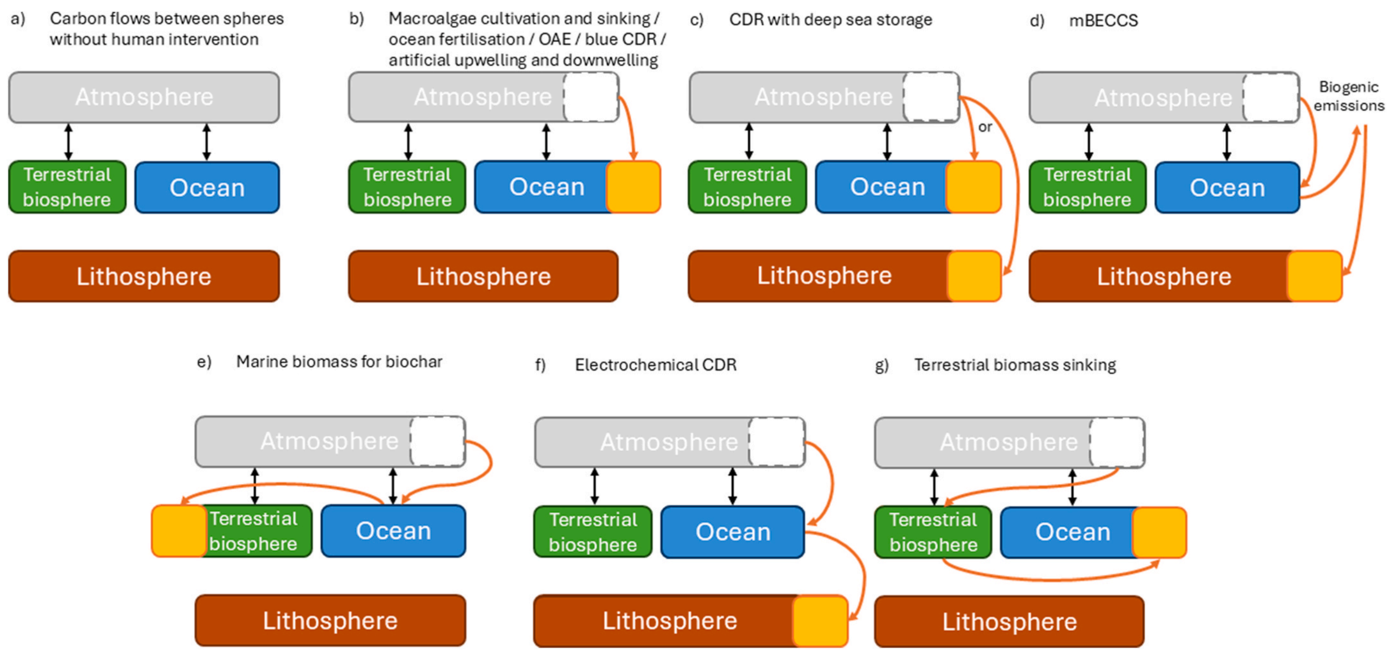

Fig. 2. Schematic representation of the changes caused by OCDR to the carbon flows between spheres. Design inspired by Smith et al. [4]. Slower carbon flows between spheres are not represented.

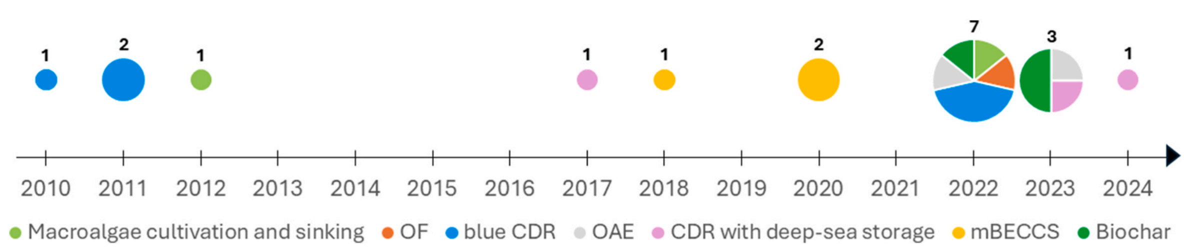

Fig. 3. Timeline of publication of the reviewed OCDR LCAs (through June 2024). The numbers represent the total number of publications found for each year.

it separately from the LCA.

Functional unit. Coleman et al. [32] use an FU of tonne of CO_2-eq. emitted per year. This is an unusual FU in LCA, as this would mean that all the inputs are scaled to a single impact. N'Yeurt et al. [33] do not explicitly report an FU but report their results per megagram (Mg) of 'bio-CO_2' stored, that is, CO_2 released during anaerobic digestion, in contrast to 'combustion CO_2' released during biomethane combustion.

Multifunctionality. No multifunctional processes are reported when macroalgae are solely cultivated to be sunk, as in Coleman et al. [32]. The system in N'Yeurt et al. [33] leads to the co-production of biomethane energy and nutrients, which is handled by substitution.

Environmental impact categories. Both LCA studies only assess the contribution of the system to global warming and do not include other environmental impact categories.

Uncertainty. Neither reviewed studies report uncertainty regarding parameters, modelling, or choices. N'Yeurt et al. [33] report variability in productivity across macroalgae species and in optimal harvest frequency across climates and deal with both by using a conservative value.

3.2. Ocean fertilisation

3.2.1. General description

Ocean fertilisation enhances the ocean's biological carbon pump. Macronutrients (e.g., phosphorus (P), nitrogen (N) or silica (SiO_2)) and/or micronutrients (e.g., iron (Fe)) are spread to the ocean surface in regions with limited nutrient availability. Nutrient release enhances phytoplankton growth, increasing DIC uptake by phytoplankton biomass via photosynthesis. Carbon is eventually passed on to other marine organisms through predation. Part of this carbon is eventually sequestered in ocean sediments when phytoplankton and their predators die and sink into the deep ocean. Net carbon removal occurs when DIC deficiency in seawater is re-equilibrated by atmospheric CO_2 drawn [6, 11].

3.2.2. LCA

We identified only one LCA: Babakhani et al. [34]. They investigated using engineered nanoparticle nutrients for ocean fertilisation.

Study goal. To assess the potential of these nanoparticles, Babakhani et al. [34] assess their environmental impacts in an LCA and their costs using life cycle costing (LCC). They investigate their toxicity risk for marine ecosystems via a literature review. Whereas the geographic scope is not mentioned in their LCA, Babakhani et al. [34] specify in their LCC that the engineered nanoparticle production takes place in China and the distribution to the ocean in the Southern Ocean.

System boundaries. Babakhani et al. [34] adopt a cradle-to-grave approach, from engineered nanoparticle production (including raw material acquisition), polymer coating, nanoparticle transportation and distribution to the ocean surface to the "monitoring of the subsequent impacts". However, it is unclear whether this latter stage refers to verifying phytoplankton bloom, the sinking of the biomass or potential environmental consequences.

Functional unit. Babakhani et al. [34] use 1 kg of engineered nanoparticles delivered to the ocean and monitored.

Multifunctionality. Babakhani et al. [34] report no multifunctional processes in their system.

Environmental impact categories. Multiple midpoint impact categories are included ($n = 18$) alongside global warming, of which two relate to marine environments: marine eutrophication and marine ecotoxicity. Babakhani et al. [34] display the results for the other categories in their SI but do not discuss their implications.

Uncertainty. The authors estimate uncertainties in their results by performing a Monte Carlo (MC) simulation on each input parameter. They also acknowledge a difference in LCA results if the technology is assessed at a laboratory scale of production or on an industrial scale. Technology variability is assessed by studying five different types of engineered nanoparticles and several synthesis methods of nanoparticles.

3.3. Blue carbon dioxide removal (blue CDR)

3.3.1. General description

Blue carbon refers to carbon captured by coastal and marine ecosystems. They include salt marshes, mangrove forests, seagrass meadows, and kelp forests, but also ecosystems in the open and deep ocean as well as marine fauna, notably large marine organisms which hold a large amount of carbon in their biomass [6,7]. Blue CDR refers to all intentional human actions aimed at increasing the carbon sequestration capacity of these ecosystems [26]. This includes creating new ecosystems (e.g., afforestation), restoring previously existing ecosystems (e.g., reforestation), and expanding existing ones. Although The National Academies Sciences Engineering Medicine (NASEM) [6] also includes protecting ecosystems, this does not fit our definition of CDR, as this preserves already existing carbon sinks but does not lead to additional carbon removal.

3.3.2. LCA

We found six LCA case studies, all related to reforestation and restoration of coastal ecosystems. These LCAs are Chen et al. [35], Cooper et al. [22], Francis et al. [36], Moriizumi et al. [37], Sparrevik et al. [38], and Vance et al. [39].

Study goal. Of the six studies identified, only three assess the carbon removal potential of the system studied [22,35,37]. Two of these three studies also have other objectives. In Chen et al. [35], these are the assessment of additional environmental benefits from ecological restoration, notably on soil quality, and the key drivers influencing the carbon sink of the ecosystem. Moriizumi et al. [37] also evaluate social and economic aspects based on employment and cash flow generation. The other case studies (i.e. [36,38,39]) do not aim to assess carbon removal potential, and it cannot be determined based on their results whether the ecological restoration results in blue CDR. Francis et al. [36] and Vance et al. [39] conduct an LCA to assess the environmental impacts of the restoration additionally to an LCC to allow for a multi-dimension evaluation. Lastly, Sparrevik et al. [38] examine the suitability of LCA methods for assessing sediment management strategies. Regarding the geographic coverage, the studies take place in China in Chen et al. [35], in the US in Cooper et al. [22] and Francis et al. [36], in Thailand in Moriizumi et al. [37], in Norway in Sparrevik et al. [38], and in Italy in Vance et al. [39].

System boundaries. Four LCAs adopt a cradle-to-grave approach (i.e. [22,35,37,38]). In these studies, the systems under consideration consist of two main phases. The first phase includes all the life-cycle stages of material preparation necessary for ecological restoration, namely the collection and preparation of reed straw and biochar in Chen et al. [35], mangrove seed collection and cultivation in Cooper et al. [22] and Moriizumi et al. [37], and materials production required to create a layer isolating contaminated sediments in Sparrevik et al. [38]. The second main phase includes the restoration operation life-cycle stages. These are reed straw and biochar application to degraded salt marshes soil in Chen et al. [35], transportation and plantation of mangrove seedlings in Cooper et al. [22] and Moriizumi et al. [37], and capping operations and contaminant disposal in Sparrevik et al. [38]. Chen et al. [35] also include soil carbon sequestration as a last life-cycle stage. In the two other LCAs (i.e. [36,39]), the system boundaries are not clearly defined, or the LCA scope only includes more downstream stages than stages related to the ecological restoration.

Functional unit. One LCA reports the results per tonne of CO_2 stored [22]. Two LCAs use a land area-based FU (i.e. [37,38]). Two other LCAs have material-based FUs expressing their results per tonne of material applied (i.e. [35]) or collected (i.e. [39]) for restoration. One LCA, using a hybrid economic input-output (EIO) approach, uses an economic-based FU to report their results in economic value (i.e. [36]).

Multifunctionality. The two LCAs reporting multifunctional processes apply substitution (i.e. [35,39]). According to Vance et al. [39], seagrass wrack collected on the beach produces electricity, heat, and digestate. They assume the internal use of heat within the system and the use of digestate as substituting inorganic fertilisers, resulting in electricity as the only final product of the system. In Chen et al. [35], pyrolysis for biochar production also produces biogas as a byproduct. However, they do not clearly distinguish avoided emissions of biogas co-production from negative emissions of ecological restoration, as they subtract both from the total emission of the restoration to quantify the net CDR potential.

Environmental impact categories. Four papers assess their systems concerning their contribution to climate change (i.e. [22,37–39]). In the remaining two studies, Chen et al. [35] perform a CO_2 accounting of their system, whereas Francis et al. [36] only assess the contributions to climate change of the alternative scenario to ecological restoration. Only three LCAs consider other impact categories (i.e. [22,38,39]). Cooper et al. [22] and Vance et al. [39] respectively include seventeen and nine midpoint impact categories in total, which include marine eutrophication and marine ecotoxicity in both cases. The LCA in Sparrevik et al. [38] includes 19 midpoint and three endpoint impact categories, from which five have characterisation factors (CFs) adapted by the authors to the local conditions of the system. They develop CFs for sediment ecotoxicity, marine sediment occupation, and marine sediment transformation, which are not found in conventional life cycle impact assessment (LCIA) methods. Their LCIA also covers marine ecotoxicity and ecosystem biodiversity at endpoint.

Uncertainty. Four LCAs perform sensitivity analyses (i.e. [22,36,38,39]). These analyses concern lifespan and variation in mangrove density in Cooper et al. [22], hurricane frequency and attenuation rates of storm surges over wetlands in Francis et al. [36], seagrass wrack collection on the beach in Vance et al. [39], and different diesel and sediment remediation material uses in Sparrevik et al. [38]. Sparrevik et al. [38] also assess different remediation strategies in a scenario analysis and perform a MC analysis to provide uncertainty ranges to their results. Some LCAs qualitatively addressed data uncertainty (i.e. [35,39]). Chen et al. [35] mention the potential insufficient delay between restoration operation and sample collection to report the overall effects of the restoration. Vance et al. [39] assume a relationship in size between the seagrass meadow and the seagrass wrack onshore, as no previous studies established such a relationship. Cooper et al. [22] also discuss the influence of relying on secondary data from literature, noting that such data may not accurately represent the specific local conditions of their case study, thereby affecting the robustness of the results.

Regarding model uncertainties, only Sparrevik et al. [38] extensively discuss the limitations of the LCA methodology. They highlight higher uncertainty of endpoint compared to midpoint indicators, the effects of methodological choices on results, as well uncertainty arising from normalisation and weighting methods. They also mention limitations specific to using LCA to assess marine environmental impacts. For instance, sediments are typically modelled in LCA as a contamination sink rather than a source, which is problematic in studies on contaminated sediment treatments. Additionally, the impact category marine aquatic toxicity is generally lacking from LCIA methods. ReCiPe is chosen as being the only method with a marine release compartment.

3.4. Ocean alkalinity enhancement (OAE)

3.4.1. General description

Ocean alkalinity enhancement (OAE) is also called ocean alkalinisation, ocean-enhanced weathering, or ocean liming. Alkaline materials (e.g., alkaline silicate or alkaline carbonate) are spread on the ocean's surface to speed up the naturally slow-occurring rock weathering process. The alkaline materials react with DIC in seawater to form bicarbonate ions (HCO_3^-) and carbonate ions (CO_3^{2-}), providing durable carbon storage. Similar to other approaches, the seawater deficiency in DIC is re-equilibrated by the absorption of atmospheric CO_2 into the ocean, resulting in net carbon removal [6,7].

3.4.2. LCA

We found two LCAs on OAE. These LCAs are Foteinis et al. [40] and Foteinis et al. [41].

Study goal. The LCA aim in both studies is to assess the environmental impacts of the technology. Foteinis et al. [40] also investigate pathways for improving environmental performance, whereas Foteinis et al. [41] explicitly focus on the carbon footprint and the CDR potential of the technology. Both studies have a European geographic coverage, and Foteinis et al. [40] also assess a global coverage in a sensitivity analysis.

System boundaries. Both LCAs apply a cradle-to-grave perspective and define similar system boundaries, with a mining stage, a rock comminution stage (fragmentation) and a final stage where the material is spread on the ocean. Foteinis et al. [40] include four other life-cycle stages, including limestone calcination, carbon capture of emissions produced during calcination, calcium oxide hydration, and transportation of the alkaline material to the ocean. Land use and land use change required for the mining activities are also included.

Functional unit. In both studies, the FU is the removal of one tonne of atmospheric CO_2 [40,41].

Multifunctionality. No multifunctional processes are reported in either study. In their sensitivity analysis, Foteinis et al. [40] include the valorisation of the low-grade heat co-produced during CaO hydration by assuming emission reductions by replacing natural gas heating. Thus, substitution is applied, although the authors mistakenly refer to it as system expansion. In the baseline scenario, low-grade heat is not recovered and is thus cut off.

Environmental impact categories. Both studies include all midpoint and endpoint impact categories of the ReCiPe 2016 method. Related to the marine environment, this includes marine eutrophication and marine ecotoxicity at the midpoint level, and damages to ecosystems at the endpoint level.

Uncertainty. Both studies perform sensitivity analyses. These analyses include means and distances of transport as well as a shift of electricity mix towards renewable energy. Foteinis et al. [40] perform additional sensitivity analyses on electricity consumption, the type of fuel and the kinds of calcination kiln used, the geographic coverage as well, as the capture of emissions from fossil fuel burning (only CO_2 from the limestone matrix decomposition are captured in the baseline scenario). Foteinis et al. [41] conducted another sensitivity analysis on various olivine particle sizes. Regarding uncertainty in the LCA methodology, Foteinis et al. [40] highlight that results given at the endpoint level have a higher uncertainty level than midpoint results.

3.5. CDR with deep-sea storage

3.5.1. General description

Here, carbon captured from the atmosphere (i.e., through direct air capture (DAC)) is durably stored in the deep ocean [7]. Carbon can be stored in its liquid form under the seabed in underground geological formations or injected into the ocean at depth [7,42]. The durability of carbon storage depends on the depth of injection [42]. Durable storage can also occur when injected carbon reaches the seafloor and reacts with rocks to mineralise [7,42,43].

3.5.2. LCA

Three LCA case studies matched our inclusion criteria. These LCAs are Casaban and Tsalaporta [44], Caserini et al. [45], and Full et al. [46].

Study goal. Casaban and Tsalaporta [44] evaluate different candidate sites for a DAC facility with carbon storage in Ireland based on environmental impacts, specifically GHG emissions and energy consumption. The two other studies aim to assess the proposed technology's performance and feasibility, Caserini et al. [45] in the Tyrrhenian and Black seas and Full et al. [46] in Germany. They conduct an LCA to evaluate the environmental performance and combine it with a cost analysis to determine the economic feasibility.

System boundaries. The deep-sea storage system is divided into two main phases: a carbon capture phase and a carbon storage phase. In all three LCAs, the last phase includes the transport and storage of the captured carbon, with an additional CO_2 compression life-cycle stage in Casaban and Tsalaporta [44] and a monitoring life-cycle stage in Caserini et al. [45]. The first phase varies across the LCAs reviewed. It includes DAC facility construction and operation in Casaban and Tsalaporta [44], biohydrogen production from fruit waste or residues and biogenic CO_2 capture in Full et al. [46], and glass capsules production (in which to store captured carbon) in Caserini et al. [45]. Hence, the carbon capture phase is outside the scope of Caserini et al. [45] and we thus assume they use a gate-to-grave approach although not explicitly stated. Casaban and Tsalaporta [44] do not explicitly report the scope but apply a cradle-to-grave approach. Full et al. [46] claim a cradle-to-grave analysis despite the life-cycle stages for carbon capture by fruits during photosynthesis and fruit processing being excluded, as they argue these stages belong to another system (fruit juice production for instance).

Functional unit. All three LCA studies use a carbon-based FU. Full et al. [46] and Casaban and Tsalaporta [44] use 1 tonne of CO_2 removed. Caserini et al. [45] express their results per tonne of CO_2 stored, aligning with their system scope, which excludes carbon capture and hence cannot claim to remove carbon.

Multifunctionality. Caserini et al. [45] and Casaban and Tsalaporta [44] report no multifunctional processes. In Full et al. [46], the gas separation stage results in hydrogen that can be used for material production and energetic purposes, as well as in $CO_{2,}$ to be durably removed. However, it is unclear whether this process is considered multifunctional and, if so, how this is dealt with in the system.

Environmental impact categories. Two LCAs only include global warming in their LCIA (i.e. [44,46]). Caserini et al. [45] consider global warming as the most relevant category, nevertheless cover additional ones ($n = 11$), from which one relates to the marine environment (marine eutrophication).

Uncertainty. All three LCAs highlight uncertainty and variability in their results. Two LCAs perform scenario analysis (with values varied according to a worst, average and best-case scenario) (i.e. [44,45]), and one LCA conducts a sensitivity analysis (i.e. [46]). Such analyses are performed on carbon efficiency, energy mix, carbon storage locations, efficiency of other system processes, facility lifespan, energy consumption, emissions of the whole system and leakages. Casaban and Tsalaporta [44] further acknowledge that data availability was a significant challenge for their study. No uncertainty regarding the LCA methodology is reported in any LCA.

3.6. Marine biomass for bioenergy production with carbon capture and storage (mBECCS)

3.6.1. General description

Also called aquatic BECCS (ABECCS), this marine alternative to the conventional bioenergy carbon capture and sequestration (BECCS) approach takes advantage of marine biomass (specifically macroalgae or microalgae) for capturing atmospheric carbon via photosynthesis. Algae are cultivated (offshore or onshore) and harvested for bioenergy production. All emissions generated during energy production are captured and durably stored (e.g., in underground geological formations) [7].

3.6.2. LCA

We found three LCAs on mBECCS. These LCAs are Beal et al. [47], Cheng et al. [48], and Melara et al. [49].

Study goal. As the purpose of a (m)BECCS technology is the simultaneous provision of CDR and the net production of energy, all three LCAs examine whether their technology fulfils this double role by combining an LCA with an analysis of the energy return on investment (EROI). Beal et al. [47] also conduct a TEA and aim to compare their technology to other technologies with similar functions based on energy, food production, and carbon storage. Cheng et al. [48] assess the most optimal feedstock for their technology and compare performance with conventional BECCS. Melara et al. [49] evaluate the most optimal location for deploying the technology assessed in the US. Neither Beal et al. [47] nor Cheng et al. [48] explicitly specify the geographic scope of their studies.

System boundaries. mBECCS system includes three main phases: the cultivation and harvesting of biomass, the production of energy from biomass, and the durable storage of carbon emitted during energy production. We find these three phases in all LCAs reviewed. In Beal et al. [47], eucalyptus is cultivated for energy production and algae is cultivated using a portion of the CO_2 emitted during energy production. Algae can then be used to produce food or feed. Although only explicitly mentioned in Melara et al. [49], all three LCAs are from cradle-to-grave.

Functional unit. Two LCAs use a mass-based FU: Beal et al. [47] in tonnes of algae meal produced and Cheng et al. [48] in tonnes of dry-weight biomass used for BECCS. Melara et al. [49] apply an energy-based FU, expressing results per annual power demand (GWh).

Multifunctionality. Alongside carbon storage, mBECCS systems provide electricity production as a second function. It can sometimes produce additional co-products, such as algae meal in Beal et al. [47] and upgraded oil in Cheng et al. [48]. This leads to multifunctional processes. Beal et al. [47] and Cheng et al. [48] resolve multifunctionality with substitution and include avoided emissions in the total carbon removed by the technology. The system in Melara et al. [49] produces both energy and crude oil due to enhanced oil recovery (EOR). In expanding their system, they include oil combustion within their FU of energy production and related environmental impacts from oil recovery and combustion.

Environmental impact categories. All three LCAs only assess the contribution of their system to global warming and include no other impact categories.

Uncertainty. Only Melara et al. [49] perform multiple analyses to deal with data uncertainty. They conduct a sensitivity analysis of the carbon storage site to determine the most sensitive parameters of EOR and the sensitivity of the results for EROI and net carbon balance. They further perform a scenario analysis providing minimum, median, and maximum data from the literature for parameters of the stages of energy production and algae biomass anaerobic digestion. Lastly, they conduct an MC analysis to evaluate the probability of simultaneous positive EROI and net carbon removal results of the technologies assessed. They account for spatial variability by assessing three possible locations for deploying their technology in the US. The other two LCAs do not perform such analyses for uncertainty. Cheng et al. [48] only test technical variability by assessing the environmental and energy performances of the technology using different feedstocks and at different temperatures of hydrothermal treatment (HTT). None of the reviewed studies report uncertainty regarding LCA modelling.

3.7. Marine biomass for biochar production

3.7.1. General description

Biochar is a carbonaceous material produced from biomass via thermochemical conversion with limited oxygen. This is an approach that has been well-studied for land-based biomass [50]. Biochar is then applied to soil as an amendment, remaining stable over long periods, increasing crop yield and removing soil pollutants [51]. As an OCDR, marine biomass produces biochar (mainly algae, which capture carbon during photosynthesis) [52].

3.7.2. LCA

We found three LCAs for this OCDR approach. These LCAs are Cole et al. [53], Lian et al. [54], and Wen et al. [55].

Study goal. Both Cole et al. [53] and Wen et al. [55] assess the feasibility of the technology by assessing the environmental performance through an LCA. Cole et al. [53] also complement their LCA with a TEA to study the economic costs. Wen et al. [55] conducted lab-scale experiments to evaluate the technical feasibility of the technology. Lian et al. [54] perform an LCA (that they sometimes also call 'life cycle carbon assessment', demonstrating the authors' emphasis on carbon) to provide a quantification method of carbon sequestration from seaweed throughout their life cycle (from nursery to biochar production). The geographic scope of the study is the US in Cole et al. [53], China in Lian et al. [54], and Sweden in Wen et al. [55].

System boundaries. We observe three main system phases across the LCAs reviewed. The first phase involves algae cultivation and harvesting life-cycle stages. It can also include stages related to material preparation, such as coating manufacture and module assembly of the DAC technology in Cole et al. [53]. The second phase involves the processing of the algae biomass (in these cases, using pyrolysis). In Wen et al. [55], bioenergy production generates additional products. The third phase is biochar application as soil amendment. This last phase is missing in the LCA scope of Cole et al. [53]. Despite Lian et al. [54] and Wen et al. [55] including the three phases, only the former report a cradle-to-grave approach. The latter reports biochar as a co-product of bioenergy production, and since bioenergy utilisation is not included in the scope, the authors report a 'well-to-tank' scope.

Functional unit. A carbon-based FU is used in two LCA case studies and is expressed as per tonne CO_2 net sequestered in Cole et al. [53] and per tonne CO_2 sequestered per year (and sometimes per g C m^{-2} $year^{-1}$) in Lian et al. [54]. Wen et al. [55] use two FUs: one per management of 1 tonne dry seaweeds and one per 1 MJ of bioenergy delivered.

Multifunctionality. In Cole et al. [53], the substrate on which microalgae grow can be recycled back into the system, as well as the bio-oil produced during pyrolysis for energy needed during drying and pyrolysing. These multifunctional processes are handled by allocating all the burdens to the primary user, resulting in a burden-free use in the following processes. In Lian et al. [54], seaweed is grown for biochar as well as food production. However, the latter is cut off from the study as the authors argue it does not take part in the seaweed carbon sequestration potential. Lastly, the system in Wen et al. [55] produces multiple products depending on the scenarios (heat, electricity, steam) that are re-used within the system. This is managed by substitution, and they subtract the avoided environmental burden from the total emissions of the system.

Environmental impact categories. All three LCAs focus on assessing the GHGs emitted and removed by the technology. Cole et al. [53] and Wen et al. [55] only assess the contribution of the system to global warming, whereas Lian et al. [54] only conduct a carbon footprint of the technology (as explicitly said in their conclusion). None includes other environmental impact categories.

Uncertainty. Cole et al. [53] perform a scenario analysis (with conservative, baseline, and optimistic values) on the carbon capture rate of algal cells and harvest time, which are the two parameters to which the LCA results are the most sensitive in their sensitivity analysis. The authors also consider the temporal variability of the technology, with the DACCS facility estimated to be incrementally constructed and reaching full capacity after five years. Lian et al. [54] deal with the uncertainty of carbon release during offshore algae cultivation by using the minimum value to obtain conservative carbon sequestration results. No LCAs report model uncertainty.

3.8. OCDR approaches lacking LCAs

We found no LCAs for three OCDR approaches: electrochemical ocean-based carbon dioxide removal (electrochemical OCDR), artificial upwelling and downwelling, and terrestrial biomass sinking.

3.8.1. Electrochemical ocean-based carbon dioxide removal (electrochemical OCDR)

In electrochemical approaches, sometimes called electrochemical direct ocean capture, CDR is achieved by using electricity in chemical reactions to alter the pH of seawater [7,56]. These electrochemical processes create acidic and basic conditions in seawater. CO_2 can be extracted from the acidic stream to be durably stored, whereas a basic stream can be rereleased to the ocean to increase its alkalinity and/or can be used to precipitate solid carbonates before releasing them into the ocean for increased alkalinity. This alkalinity increase in seawater leads to the transformation of DIC into stable forms (bicarbonate ions and carbonate ions), providing durable carbon storage [6,7]. Current research mainly focuses on optimisation strategies, notably their costs, rather than environmental assessment [6].

3.8.2. Artificial upwelling and downwelling

In artificial upwelling, water abundant in nutrients from the deep ocean is pumped to the ocean's surface, enhancing phytoplankton photosynthesis and the consequent ocean biological carbon pump [57,58]. In artificial downwelling, waters at the ocean's surface rich in carbon and biomass are pumped down to the deep ocean where carbon is considered durably stored [6,7]. This OCDR approach remains theoretical, with high uncertainties regarding its actual CDR potential and potential environmental impacts at a large-scale deployment [6,7,59–61].

3.8.3. Terrestrial biomass sinking

Similarly to the sinking of macroalgae, the intentional sinking of terrestrial biomass (e.g., plant residues or waste from agriculture production) into the deep ocean or at the anoxic bottom of large marine water bodies has been suggested as a potential approach for durable storage of carbon [7,62,63]. More research is generally needed to assess its CDR potential, the time horizon of the sequestration and the feasibility for large-scale deployment [62,63]. For example, much remains uncertain about the fate of methane in the deep ocean or the response of benthic microbial communities to increased carbon levels [62].

4. Discussion

OCDR approaches remain largely unexplored in LCAs, with only 20 LCA case studies identified. Research on LCA for OCDR is relatively recent, with the first LCA case study published in 2010 and more than half of all identified case studies published within the last three years. The first LCAs conducted were published on blue CDR in the early 2010s, and although the system studied qualifies in their technical description as a CDR approach, they were not referred to as such and were conducted for other reasons than assessing their CDR potential. More LCAs on OCDR are likely as interest in these technologies grow [25]. Further LCA research is needed to improve our knowledge of their environmental impacts, as recommended in a previous LCA review on CDR [20].

4.1. Common LCA focus area

4.1.1. Goal and scope definition

Whereas the LCAs reviewed mostly aim at assessing the OCDR feasibility regarding net carbon removal, many have additional goals. Economic profitability is a major concern in most studies ($n = 8$), which additionally performed an economic analysis, such as LCC or TEA, to assess the costs and potential for carbon credit generation. For energy-producing OCDR approaches like mBECCS, net energy production is also assessed ($n = 4$), notably through an analysis of EROI ($n = 3$). However, some LCAs are included in our review because the technologies studied fit our OCDR definition, even though the authors do not refer to their approach as CDR. In these cases, the LCA is conducted for other purposes than investigating the CDR potential of the technology. This is mainly the case for the blue CDR LCAs, from which only three aim to assess the CDR potential of ecological restoration. Whereas other goals can be investigated, LCA of OCDR approaches should focus on evaluating the net carbon removal potential and potential environmental side-effects.

Regarding geographic scope, several LCA case studies do not clearly specify their geographic coverage ($n = 4$). When it is mentioned, the studies are predominantly focused on the US, China, or Europe. As a result, specific regions, particularly in the Global South, are currently overlooked, although the potential for deploying OCDR approaches and their environmental impacts may vary significantly across regions. More broadly, local conditions play an important role and should be considered in LCA case studies. Oceanic conditions differ across regions, with some areas more affected by chemical pollution, nutrient runoff, plastic waste or overfishing, all of which could influence CDR effectiveness and may act as additional environmental stressors influencing the overall environmental performance of the technology.

4.1.2. System boundaries

Most LCAs on OCDR use a cradle-to-grave perspective ($n = 15$). As previously indicated [63], determining whether a technology results in net carbon removal relies on a cradle-to-grave assessment [20]. Every lifecycle stage can lead to environmental impacts and contribute to carbon emissions, reducing the overall CDR potential, so cradle-to-grave perspectives in CDR LCA studies are essential.

4.1.3. Functional unit

Despite prior calls for a common FU to enable comparison across CDR LCAs [21], we find considerable variety in the FUs employed in the LCAs reviewed. Some FUs relate to the product delivered ($n = 6$), such as energy produced ($n = 2$) or biomass used in the system ($n = 3$) or to land area in blue CDR ($n = 2$). However, the choice of the FU should reflect the main function of an OCDR approach. Prior LCA reviews have already called for adopting carbon-based FU for CDR approaches [17,20,21]. We also find one LCA [32] using an FU of one tonne of CO_2 emitted. Such a FU is not appropriate in LCA, and instead refers to the impact category of global warming in LCIA.

Most studies ($n = 9$) present their results per tonne of CO_2 removed or stored. Despite being in accordance with recommendations from previous reviews [17,20,21], the net carbon removal of a CDR approach should not be stated in the FU as it can only be determined based on the LCA results. We further observe that, of these LCAs using a carbon-based FU, none consider the time horizon nor the location of carbon storage. Although the IPCC definition states that carbon can be considered removed when stored durably [5], the time horizon that should be guaranteed to claim durable storage remains unclear. This vague definition of durability is also noticeable in scientific reports on CDR and OCDR, from 'decades to millennia' [4] to 'for some period of time' [6]. For clarity, the time horizon of the carbon storage should be specified in the FU. Moreover, the location of the carbon storage should also be mentioned, as while the majority of OCDR approaches have as carbon destination the deep ocean, carbon can end up in other media in some cases, such as in soil in mBECCS.

4.1.4. Multifunctionality

We find that multifunctional processes and the method applied to address multifunctionality are not clearly reported across studies. Typically, macroalgae cultivation and sinking, mBECCS, and marine biomass for biochar production have processes delivering multiple functions, such as energy production in addition to carbon removal. Multifunctionality can be solved using different methods, each of which can influence the results. Hence, it is crucial to report explicitly the assumptions made.

In the studies where we find multifunctional processes ($n = 9$), substitution is the most applied option ($n = 6$), but this method can lead to confusion between avoided with negative emissions. Substitution maintains a single function for the process by subtracting the environmental impacts of the co-product(s) production from the total process impacts. These subtracted impacts are considered avoided environmental burdens as they are assumed to prevent the production of products with the same function [65–67]. For CDR approaches, these avoided emissions are often not distinguished from negative ones. Avoided emissions differ from negative emissions, as they do not represent CO_2 emissions directly removed from the atmosphere [64]. This leads to a potential overestimation of the CDR potential and depends highly on the modeller's choice in selecting the substituted product. Others have already highlighted this issue for LCAs of CDR approaches [20,64]. Sensitivity analysis should be conducted to evaluate the impacts of different methods to handle multifunctional processes on the LCA results. However, none of the LCAs reviewed performs such an analysis.

4.2. Data quality and assumptions

4.2.1. Data sources

Due to a lack of empirical data, most LCAs reviewed based their assessment of OCDR performance on a hypothetical case ($n = 16$). Most data came from literature ($n = 17$), and only half used empirical data from lab or pilot projects ($n = 9$). Additional data sources are authors' own calculations ($n = 7$), models ($n = 1$), field surveys ($n = 1$), and interviews ($n = 1$). A lack of empirical data when conducting LCA potentially leads to the misrepresentation of the OCDR approach environmental effects and consequent flawed estimations of the overall environmental performance of CDR.

4.2.2. Prospective LCAs and scale-up challenges

Once empirical data is collected, prospective LCAs also face the issue of scaling data to represent the future state of the technology once deployed on a large scale. LCA models typically scale up environmental impacts linearly [68]. This means that the LCA model calculates the increase of environmental impacts proportionally to the increase in product output [69]. However, this is often not true in reality, as the same technology at different TRLs will have different environmental performance for the same product output due to economies of scale, improvements in technical efficiency, and industrial synergies [69,70]. Hence, the relationship between technologies and environmental impacts will likely not be non-linear.

Interdependencies within technologies can emerge when deployed on a large scale, which may not be captured in small-scale studies. For instance, a large offshore macroalgae farm might underperform due to competition for light and nutrients, unlike a pilot-scale farm. These non-linear relationships are a problem, particularly for assessing the future environmental impacts of emerging technologies, as data are typically from pilot-scale experiments and not necessarily representative of performance at scale [69]. Recent work has developed a decision tool to help LCA practitioners apply the most appropriate scaling methodology to their emerging technology [71]; however, more research is needed for the appropriate scale-up of data in prospective LCA.

It is also worth noting that prospective LCAs use prospective LCI databases to project background processes into the future state of analysis. These databases are generated from scenarios derived by integrated assessment models (IAMs) representing shared socioeconomic pathways (SSPs). Such scenarios serve more as an exploratory than a predictive analysis and are built on a set of assumptions that should be carefully considered when conducting prospective LCAs.

4.3. Impact categories in LCIA and marine environment relevance

4.3.1. Focus on global warming and GHGs

The LCAs reviewed focus on the contribution of the OCDR studied to global warming and tended to overlook other impact categories. Global warming as an impact category allows for evaluating the CDR potential of a technology [19] and is almost always included ($n = 17$). However, in many cases ($n = 10$), this is the only impact category included in the LCIA. In two LCAs (i.e. [35,54]), the study is even further restricted to only accounting for carbon/CO_2, omitting other GHGs. A restricted inclusion of impact categories has already been observed as a problem in LCA for CDR approaches in general [20,21].

This omission of impact categories also concerns those related to the marine environment. While three impact categories currently exist in most LCIA methods, the reviewed LCAs rarely included them in their assessment: marine eutrophication ($n = 5$) and marine ecotoxicity ($n = 5$) at a midpoint level, and damage to ecosystems ($n = 2$), which encompasses damage to terrestrial, freshwater, and marine species, at an endpoint level. Incorporating marine impact categories in OCDR LCAs is crucial, as these technologies will be deployed in marine environments and may impact them.

4.3.2. Marine environment indicators

Including existing marine impact categories remains insufficient for assessing the potential environmental impacts of OCDR approaches. Initially, the development of LCA aimed at evaluating the impacts industries developed on land have on terrestrial and freshwater ecosystems, and the current LCIA methodology at large remains underdeveloped for impacts on marine environments [72]. Whereas current LCIA methods only include the three impact categories mentioned above for marine environments, seven factors have been identified driving marine biodiversity loss [73,74], namely climate change, ocean acidification, eutrophication-induced hypoxia, damage to the seabed, biotic resources overexploitation, invasive species, and marine plastic pollution. Of these, the majority lack fate and exposure factors [72]. As a result, many impacts occurring in the marine environment, including those potentially arising from the future large-scale deployment of OCDR approaches, remain unquantifiable by current LCA models. One LCA reviewed (i.e. [38]) addresses this issue by developing their own CFs adapted to the local conditions of their system for impact categories not found in conventional LCIA methods (sediment ecotoxicity, marine sediment occupation, and marine sediment transformation). Nevertheless, developing and implementing generic CFs for more marine impact categories in LCIA methods is essential to enable their assessments in all OCDR LCAs.

Additionally, LCA currently models the ocean as a single compartment, overlooking its substantial spatial heterogeneity. Marine environments greatly vary by location, depending on whether they are located in coastal or offshore, pelagic or benthic zones. This spatial variation in marine conditions results in distinct ecosystems and spatial fluctuations in biodiversity [75]. Consequently, impacts on biodiversity are likely to differ across these local marine environments. These spatial differences are not yet captured in LCA and require the development of marine sub-compartments, as already advocated in a recently published framework [76].

4.4. Uncertainty

4.4.1. Sources of uncertainty

Despite the substantial uncertainties associated with OCDR LCAs, we generally observe poor uncertainty assessments in the reviewed case studies. Uncertainty, notably due to the scarcity of empirical data, is inherent to prospective LCAs on emerging technologies [16]. This uncertainty is exacerbated for technologies deployed in the marine environment, like OCDR approaches, as the physical, chemical, and biological systems in the ocean are highly dynamic. It is, therefore, challenging to distinguish naturally occurring changes from changes arising from anthropogenic perturbations [77,78].

For example, residual times of carbon in marine environments are highly influenced by local conditions, currents, and organisms present [77]. Monitoring the impact of a CDR approach deployment is further challenged by the rapid dilution of the CDR signal below detectable levels and by its transport away from the deployment site [77,78]. Even with improved data collection techniques, fundamental limits in remote sensing will always remain that will never allow for the complete quantification of long-term carbon storage.

However, we find that the uncertainty of carbon storage durability is rarely addressed despite being particularly critical in cases of non-geological storage. Subsequently, a functional unit based on the removal of carbon dioxide over a set time will always have inherent uncertainties, which will influence the environmental impacts resulting from OCDR approaches. Moreover, the prospective nature of LCAs on OCDR approaches introduces uncertainties arising from evolving background systems (e.g., energy systems) and potential unforeseen future impacts ('unknown unknowns') that are not considered. Hence, large data uncertainties are associated with OCDR LCAs that must be addressed.

4.4.2. Uncertainty assessment

Less than half of the reviewed LCAs perform sensitivity analyses ($n = 9$), and all the analyses conducted concern sensitivity to data and not to modelling choices. Modelling choices in LCA are unavoidable and lead to uncertainty [30]. Uncertainty due to choices and parameter uncertainty can be addressed in sensitivity analyses, such as in one-at-a-time (OAT) approaches. OAT sensitivity analysis evaluates the parameters influence on the overall LCA results by varying one variable at a time and reporting the observed variation in outcome [16,66]. They can also evaluate the impacts of alternative data and methods on the results [66].

Scenario analyses are done in LCAs of OCDR approaches only in a few cases ($n = 5$). Such analyses identify plausible states of the studied system (e.g., best- and worst-case scenarios) and quantify the likely LCA result range for each scenario [79]. Furthermore, advanced LCA analyses can simultaneously analyse different uncertainties in unit process data and CFs [80], allowing for the systematic quantification of data variability and uncertainty, modelling inaccuracy, and providing a degree of confidence behind conclusion [16,81]. Such analyses are typically achieved using stochastic propagation methods [30,66], like MC simulations, implemented in most LCA software [80]. MC analysis sample variables stochastically for a given distribution over a given number of replications, resulting in a range of LCA results [30,80]. When coupled with a global sensitivity analysis, sensitive variables can be determined, and data improvement potentials can be spotted. However, a very low number of LCAs perform an MC analysis ($n = 3$). Many LCAs only discuss qualitatively some uncertainty issues, and others do not report uncertainty in any form. Model uncertainty is rarely reported, which is nonetheless an important source of results influence, as we explained in Section 4.1.6. Uncertainty and LCA limitations must be communicated to nuance the LCA results.

5. Recommendations

In the discussion, we addressed many limitations regarding assessing the environmental performance of OCDR approaches via LCA. Currently, LCA cannot provide a complete assessment of these technologies when deployed at a large scale. The question may then arise whether LCA is the most appropriate method to assess OCDR environmentally. In that case, other methodologies, such as risk assessment, should be evaluated. Nevertheless, we provide guidance on improving future LCAs of OCDR approaches. Our recommendations should be applied in addition to ISO standards (ISO 14040 and 14044), which provide fundamental practices for conducting LCAs and are currently poorly applied in LCAs of OCDR approaches.

5.1. Precautions in comparative assessment

We strongly recommend not comparing environmental LCA results of OCDR approaches across studies in decision-making processes. This aligns with ISO guidelines, which advise against cross-study comparisons when context and assumptions are not equivalent [81]. As shown in this review, LCAs of OCDR approaches vary in their systems studied and scopes. Additionally, these assessments are associated with important uncertainties. Comparison of LCA results should be limited to the same OCDR approaches conducted similarly, such as the large-scale deployment of two OAE approaches only varying by the type of alkaline material used.

Additionally, we advise caution when integrating OCDR approaches into IAMs. As attention to these technologies grows, there will likely be a concomitant interest in parameterising them within IAMs to provide a broader suite of CDR options to policymakers. However, as demonstrated in this review, the current state-of-the-art research precludes their use in large-scale, politically influential models such as IAMs. Even if our understanding of OCDR technologies improves significantly, careful consideration will remail essential when incorporating them into IAMs to avoid repeating the same mistakes observed with BECCS, where many IAM trajectories overly relied on this CDR technology without adequately considering biophysical and environmental constraints [82].

5.2. CDR-focus study goal

LCA on OCDR approaches should aim at assessing the net carbon removal potential of the system once deployed at an industrial scale and, more broadly, the overall environmental performance of the OCDR, notably regarding environmental impacts on the marine environment as they will be deployed in oceans.

Additionally, we advise providing the technical readiness level (TRL) with information on the state of the OCDR and the uncertainty associated with its deployment. The TRL, which is a value given to inform on the technology maturity [83,84], is rarely included in current LCAs of OCDR, which at best only briefly discuss the readiness level of the OCDR.

5.3. Cradle-to-grave system boundary

As previously recommended [17,20,85], we advise using a cradle-to-grave perspective in LCAs on (O)CDR approaches to include all fundamental processes, from raw material extraction to durable carbon storage, and to capture all major environmental impacts of the technology lifecycle. Only by adopting this scope can it be determined whether the OCDR approach could potentially result in net carbon removal [64].

5.4. The importance of data collection

Collecting more empirical data for economic and environmental flows is fundamental. Whereas OCDR credits are already being deployed and sold [86], as well as OCDR protocols, are being developed and implemented [87–89], the understanding of OCDR mechanisms and their potential environmental effects remains limited. Particularly, data collection for environmental flows is essential to explore a more holistic set of impact categories and support more LCIA methods. LCAs on OCDR approaches should ideally be conducted in collaboration with pilot projects on these technologies, as this could reduce data uncertainty and improve the collective knowledge of different approaches.

5.5. Functional unit

The choice of the FU should reflect the main function of an OCDR approach, which is the net removal of atmospheric CO_2. However, as the net removal of an OCDR approach can only be determined based on the

LCA results, a more appropriate FU can be phrased as the storage of one tonne of atmospheric CO_2. We advise to apply as FU the storage of one tonne of CO_2 from the atmosphere over a specified time in a specified medium (e.g., one tonne of atmospheric CO_2 stored for 100 years in mangrove biomass) for clarity. However, it should be remembered that the global warming impact category in most LCIA methods relies on a 100-year time horizon impact indicator. As a result, the added benefit of a CDR approach storing carbon for more than a century would not be captured.

5.6. Transparency in solving multifunctionality

Multifunctional processes and the method applied should be explicitly stated for transparency and reproducibility. The method chosen should be consistently applied. To prevent confusion with negative emissions, avoided emissions should not be subtracted from the total emissions of the system and should be reported as a side benefit of the OCDR approach substitution [20,65,66]. We recommend including a sensitivity analysis with an alternative method to assess the sensitivity of the LCA results to different multifunctional methods.

5.7. LCIA: inclusion of multi-impact categories and further methodological developments

In LCA, OCDR approaches should be assessed over various environmental impacts to identify potential environmental trade-offs resulting from their large-scale deployment. The chosen LCIA methods need to be supported by appropriate unit process data and should include all three impact categories existing in LCA for the marine environment, namely marine eutrophication and marine ecotoxicity at the midpoint level and damage to ecosystems at the endpoint level. However, as aforementioned, the LCA method's capacity to assess marine impacts remains limited. Fate and exposure factors for additional marine impact categories are therefore warranted. Potentially damaging effects not grasped by the LCIA should be reported qualitatively when their quantification is impossible. Potential environmental impacts are reviewed per OCDR approach in the NASEM report [6], and an update summarising our knowledge of these impacts is currently being developed by Ward et al. within the context of a European-funded project on OCDR approaches (SEAO2-CDR) [90].

Moreover, future research in LCA should focus on dividing the marine compartment into appropriate sub-compartments, both vertically (surface, pelagic, and benthic) and horizontally (coastal and deep ocean) [76,91,92]. This would allow for the development of compartment-specific and preferably spatially resolved CFs. Until these advancements are made, the lack of marine spatial differentiation in current LCA models should be explicitly acknowledged in OCDR LCAs. Furthermore, environmental flows without CFs in the LCIA should also be clearly reported.

5.8. Addressing uncertainty

Data uncertainty should be addressed whenever possible by defining empirical uncertainty ranges for unit process data or, when unavailable, on proxies and conducting extensive uncertainty analyses. Sensitivity analyses can also be conducted to identify a system's boundary conditions, such as determining the parameter values that shift the system from a net carbon remover to a net emitter.

We recommend conducting multiple sensitivity analyses. We reiterate the previous recommendation of performing a sensitivity analysis with alternative multifunctional methods [19,65], especially when substitution was chosen. A sensitivity analysis with an alternative LCIA methodology can also evaluate the sensitivity of the results to modelling choice. Additionally, for OCDR approaches with a risk of carbon leakage or reversibility to the environment, the sensitivity of the results to the storage security can be tested in a sensitivity analysis. More sensitivity analyses can be made, notably using alternative CFs for one impact category [16].

Scenario analyses should also be conducted. A relevant choice of scenarios is specific to each study and cannot be standardised across LCAs [93], but can include a baseline and extreme scenarios by varying the parameters identified as the most sensitive [80]. Scenario analysis can also be performed by evaluating the impact of different plausible states of the background system on results. One such analysis often done in LCA is by varying the energy system, from a fossil fuel-based system to larger shares of renewable energy in the energy mix, for instance Refs. [66,94].

We strongly recommend discussing the LCA results alongside the sensitivity, scenario, and uncertainty analysis results. Moreover, when uncertainty cannot be quantified, it should at least be reported qualitatively. Technology uncertainty and potential environmental side-effects on the OCDR approach should also be reported. Finally, we emphasise the importance of acknowledging and reporting the limitations of the LCA methodology in quantifying environmental consequences in aquatic environments [38], especially marine ones, which prevents a complete assessment of the environmental performance of OCDR approaches.

6. Conclusions

Achieving global climate targets is expected to rely heavily on the near-future large-scale deployment of CDR approaches, including OCDR. However, many unknowns remain regarding their CDR potential and overall environmental performance. We evaluate the current state of knowledge and practice of LCAs on OCDR approaches. We find that the literature is recent and remains limited, which does not allow for a complete understanding of their future environmental performance once deployed on a large scale and their potential contribution to climate targets. It must also be emphasised that CDR approaches cannot substitute for urgent and substantial emissions reductions, and uncertainties persist regarding their large-scale viability.

Current LCA models do not capture the overall impacts of OCDR approaches on the marine environment. This raises the question of whether LCA is the most suitable approach for the environmental assessment of OCDR. If not, other methodologies, such as risk assessment, should be considered. Nevertheless, LCA can be conducted to provide initial insights into the environmental hotspots of the technology for design improvement, identifying knowledge gaps, and guiding future research.

We provide recommendations for improving future LCAs of OCDR approaches, such as adopting a cradle-to-grave perspective, using an FU of one tonne of atmospheric CO_2 stored over a specified time in a specified medium, reporting avoided emissions due to multifunctionality solved by substitution separately from negative emissions, choosing an LCIA method including impact categories related to the marine environment, and conducting extensive sensitivity and uncertainty assessments. LCA practitioners should collaborate with pilot projects on OCDR to increase empirical data collection. Future research should also aim at improving the LCA methodology for assessing environmental effects in marine environments, by notably developing additional marine impact categories in the LCIA and dividing the marine compartment into relevant sub-compartments.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2025.116091.

Data availability

All data used can be found in the Supplementary Information.

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