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Life cycle of carbon in macroalgae for various products

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1.0 Overview

This paper seeks to understand the life cycle and permanence of carbon sequestration for the many possible products of offshore cultivated macroalgae, compared to natural growth, habitat restoration, and intentional sinking. The paper will systematically review existing life cycle analyses (LCAs) for various macroalgae products to identify information gaps and compare the carbon sequestration potential throughout each product life cycle. The sequestration potential of macroalgae is well documented (e.g. Chung et al., 2011; Krause-Jensen & Duarte, 2016) but the permanence of the capture is not understood for harvested macroalgae or end products, which may or may not release the stored carbon dioxide in processing or consumption. This information is necessary to avoid overestimating the benefit and impacts of federal investment in large-scale seaweed aquaculture.

The goal of this report is to:

- Review published LCAs for various macroalgae products and uses
- Identify knowledge gaps (experiments and monitoring) to understand the flow of carbon on various time scales
- Develop preliminary ranking of macroalgae products by carbon capture effectiveness and permanence

2.0 Introduction

Most future emissions models predict that carbon dioxide removal (CDR) is needed to complement emission reductions to meet the goals of the 2015 Paris Agreement. The Intergovernmental Panel on Climate Change Special Report in 2018 as well as the most recent 2021 report both emphasize this, predicting that removal will need to be on the order of hundreds of billions of tons by the end of the 21st century (IPCC 2018, 2021). For CDR to be effective, the carbon that is captured needs to be sequestered on a timeframe that enables effects on greenhouse gas emissions. Permanent capture is typically considered to be 100 years (California Air Resources Board, 2018), though there are some that argue for a broader definition of temporary capture that could still have value for reducing the impacts of greenhouse gases, though discounted (CarbonPlan & Climateworks, 2020; Herzog et al., 2003; Kim et al., 2008). Regardless, an understanding of the permanence of carbon capture in considering various technologies or future investments is necessary to provide realistic predictions for outcomes of investments, and influence the governance of CDR technologies (Boetmtcher et al., 2021).

Several key terms are often used in discussions about carbon capture, and are defined below for clarity. An understanding of the differences between these terms enables realistic comparisons of technologies.

- ***Carbon dioxide removal***: "Anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical sinks and direct air capture and storage, but excludes natural CO_2 uptake not directly caused by human activities." (IPCC, 2018)
- ***Carbon sequestration/storage***: used interchangeably to describe the ultimate destination of the carbon removed, and important factor in permanence (Bergman & Rinberg, 2021)
- ***Negative emissions***: total emissions permanently captured by technology in excess of the emissions from processes required for removal (energy, transportation, land use changes, etc.) (Fuss et al., 2018; Minx et al., 2018; Tanzer & Ramírez, 2019; Terlouw et al., 2021)
- ***Avoided emissions***: due to system expansion or substitution of components or processes. These emissions do not represent permanent removal of GHGs and need to be considered separately from carbon capture and negative emissions calculations (Terlouw et al., 2021)

This paper focuses specifically on the sequestration of carbon dioxide (as opposed to other forms or carbon or greenhouse gases, such as methane [CH_4]). Marine carbon dioxide removal (mCDR) technologies are an evolving subset of carbon capture technologies that include both biological and chemical pathways (Energy Futures Initiative, 2020; Intergovernmental Oceanographic Commission, 2021). This paper looks at biological carbon capture, narrowed on macroalgae cultivation as a mCDR strategy.

Macroalgae include a variety of seaweeds and kelp, typically classified into brown, red, and green algae. The average carbon sequestration potential of macroalgae is around 1.8 kg C m-1yr^{-1} (Kumar et al., 2017), with some estimates that current macroalgae globally could sequester about 173 TgCyr^{-1} (Krause-Jensen & Duarte, 2016). The focus of this review centers on kelp, which is a category of brown algae often found in temperate waters. Interest in farming kelp in the United States has been growing in the last decade, with many new farms seeking permits and increasing in size. The U.S. Department of Energy has made substantial investments in kelp farming in recent years, including the ARPA-E MARINER project focused on macroalgal biofuels, and various projects under the Water Power Technologies Office (WPTO) surrounding the integration of marine energy with aquaculture for processing (Rinker et al., 2021), monitoring (Molly Grear’s FY21 WPTO Seedling), and providing power for offshore farm facilities (topics under the Powering the Blue Economy Initiative).

While significant research has been done on macroalgae as an mCDR strategy (e.g., (Ocean Visions, 2021; Chung et al., 2011, 2013; Froehlich et al., 2019; Krause-Jensen & Duarte, 2016; Duarte et al., 2017; Zhang et al., 2017; Duarte et al., 2005; Krause-Jensen et al., 2018), the permanence of the carbon sequestered is not well understood once the kelp is harvested and utilized, which may or may not release the stored carbon dioxide through processing or consumption. This paper is unique in that it presents the first review of life cycle analyses (LCAs) for products made from macroalgae and the permanence of carbon captured in those products. Life cycle analysis is a well-established approach for assessing the sustainability and environmental impact of products and process. Some systematic reviews of LCAs have been undertaken for algal biofuels (Chamkalani et al., 2020; Chiaramonti et al., 2015; Collet et al., 2015) and carbon capture technologies (Terlouw et al., 2021), but this is the first review of macroalgal products for carbon sequestration.

3.0 Methods

Studies for this literature review were collected from iterative, nonsystematic searches on both Google Scholar and Scopus for the terms “life cycle analysis AND (macroalgae OR kelp OR seaweed)”, and “carbon AND (macroalgae OR kelp OR seaweed)”. From this, papers were identified that presented a distinct LCA that included some analysis of a seaweed project. Review of each paper considered specific products, species of macroalgae, methods of LCA utilized (including definition of functional units and impact categories), CO_2 emissions (including negative and avoided), permanence/timeframe considered for analysis, and knowledge gaps indicated in each paper (see **Appendix A** for complete table).

A recent review of LCAs performed for carbon capture technologies found many inconsistencies and shortcomings in methods, and provides recommendations for improvement including consideration of the temporal aspect of emissions in biomass technologies for carbon capture (Terlouw et al., 2021). These temporal aspects, or variations in the timing of emissions, can have significant impact on true climate change impacts (Cooper et al., 2020). Other studies from various disciplines have noted some of the weaknesses of LCA for true assessment of climate impacts, as well as noting similar temporal limitations and proposing solutions (Agostini et al., 2020; Christensen et al., 2009; Frischknecht et al., 2009; Kendall, 2012; Lueddeckens et al., 2020; Peters et al., 2011; Reijnders, 2020; Schmidt, 2009). However, LCA is still generally considered a standard approach for assessing environmental impacts over the life of a product or process, and even approaches based on estimations can be useful to inform decisions (Bala et al., 2010). For this study, the most useful metric contained in LCAs for considering carbon sequestration is the global warming potential (GWP), often measured over 100 years (GWP100) and in the units of kg CO_2 emissions equivalent (kg CO_2 e), as described by the IPCC (2021). Each LCA is conducted with a particular functional unit (FU), which is the frame of reference for performance of a system (for example, a common FU is 1 kg of final product).

4.0 Results – Life Cycle Analyses

This literature review identified 39 LCAs related to macroalgae. 33 of these utilized GWP as an impact category, though 21 of these studies (75%) did not consider carbon capture in the cultivation of macroalgae in their calculations. Most studies were done on kelp species, with fewer studies on green or red algae (Figure 2). The most work has been done on *S. latissimus* and *L. digitata*, both of which are species of kelp.

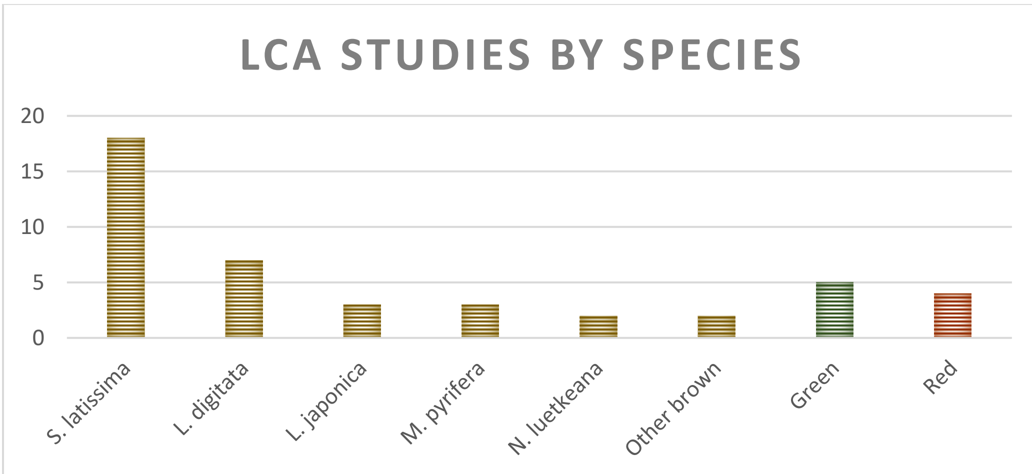

Figure 1. Species of macroalgae considered in LCAs. Note that some LCAs reviewed multiple species such that totals are greater than 100%.

Numerous products can be made from macroalgae, including biofuels, protein for humans and animals, fertilizers, commercial extracts, materials, and more. Macroalgae can also be grown without being harvested for a product, such as for habitat restoration projects or to provide habitat benefits at a farm that primarily grows and harvests other species of fish or shellfish. The distribution of LCAs for each product and usage category is shown in Figure 3. This review found that the most LCAs have been conducted for macroalgal biofuels, followed by LCAs for processes that created multiple products.

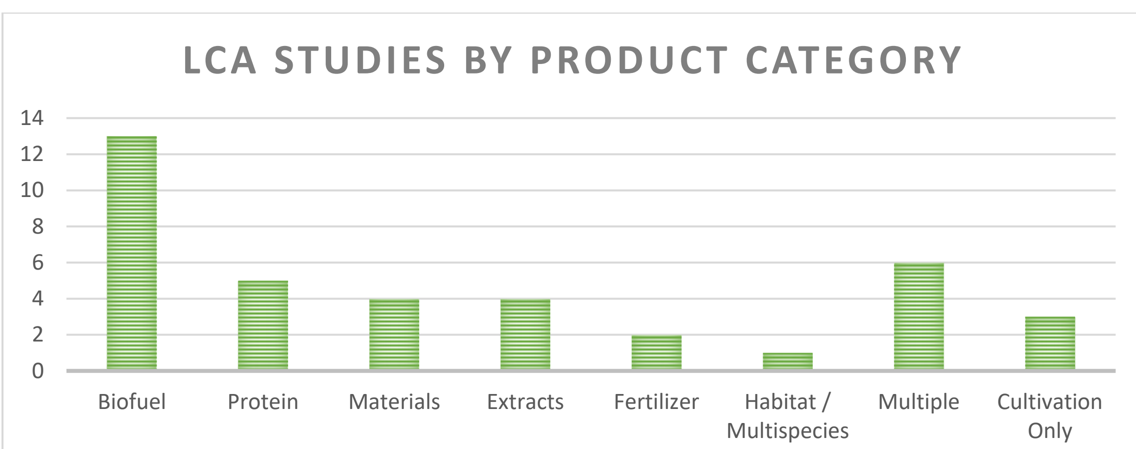

Figure 2. Number of studies reviewed for each broad product category (n = 39).

Biofuel

LCAs on biofuel production from macroalgae were the most numerous, with 13 papers solely on biofuels and included as a product in all six of the LCAs addressing multiple product categories. Biofuels from macroalgae include bioethanol, biogas, biomethane and biodiesel. Various species can be used, including species of brown, red, and green algae, though most studies (11/13) included at least one species of brown algae, with L. digitata (5 LCAs) and S. latissimus (4 LCAs) most common. The FU for each study varied greatly, including units in energy, mass, and volume (e.g., 1 MJ energy, 1 tonne of dry seaweed biomass, 1 m^3 of biogas produced, 1 km driven in a vehicle, 1 kg of feedstock, 1 GJ of biogas, 1000 L of bioethanol, 1 kW electricity). Seven of the LCAs considered carbon capture by the macroalgae in their calculations of GWP, though in many it was calculated based on simple stoichiometry or published averages ranging from 1.01 to 1.137 kg CO_2 per 1 kg dry seaweed (Aitken et al., 2014; Alvarado-Morales et al., 2013; Fry et al., 2012).

Examples of GWP results are shown below (in order of lowest GWP to highest), though the FUs and other methodological considerations make direct comparison difficult, and not recommended.

- -1870 kg e CO_2 per ha of sea cultivated (biogas and fertilizer, Seghetta et al., 2017)
- -10 kg CO_2 e per ha of sea cultivated (bioethanol and biochar, Seghetta et al., 2016)
- 13.9 g CO_2 e per MJ biogas (codigested with chicken manure, Ertem et al., 2017)
- 0.027 kg CO_2 e per MJ biomethane (Fry et al., 2012)
- 32 g CO_2 e per MJ biodiesel (coupled with biochar, where 85% of carbon captured ends up in fuel, Greene, 2019)
- 40.6 g CO_2 e per MJ biomethane (from a multispecies farm, Czyrnek-Delêtre et al., 2017)
- 51 g CO_2 e per MJ biomethane (Tonini et al., 2016)
- 0.085 kg CO_2 e per MJ bioethanol (Fry et al., 2012)
- 160 g CO_2 e per kg feedstock (co-digested with chicken manure, Ertem et al., 2017)

Protein

Many species of macroalgae can be consumed by humans either raw, cooked, or processed in another way. Protein from macroalgae can also be utilized in feed for fish aquaculture or livestock on land. GWP is utilized as a metric in nearly all of the LCAs reviewed, with FUs at various points of processing that include 1 ton of protein product, 1 kg of edible product, 0.61 t of pure protein, 1 kg crude protein, and 1 ton of seaweed protein concentrate. None of the LCAs explicitly considered carbon capture in the analysis, with one study noting that sequestration was not considered as it was assumed all carbon would rapidly return to the atmosphere (Koesling et al., 2021). Several studies noted that larger farms (~10,000 ha) had lower GWP than smaller farms (~1 ha), with ranges from larger farms reported from 2 – 142 kg CO_2 e (for various FUs) (Halfdanarson et al., 2019; Koesling et al., 2021; Philis et al., 2018).

Materials

One of the primary materials that macroalgae can be used for is packaging. This can include films, bioplastics, or lactic acid (a major component in bioplastics). All of the LCAs for bio-packaging included GWP as an impact category, reporting values ranging significantly from 0.70 to 513 kg CO_2 e for various FUs (1 kg lactic acid, 1 kg packaging, 1m^2 film). One of the two studies that considered carbon capture during cultivation added a credit of 1.47 kg CO_2 e to the final GWP for capture (Helmes et al., 2018), and the other assumed that net capture was zero due to end-of-life consumption (Ögmundarson et al., 2020).

One LCA included in this analysis describes the use of Z. marina as a building material (Widera, 2014). While technically a vascular plant and not a macroalgae, this product was described as a seaweed and thus was encountered in the literature review. It is likely that true macroalgae could have similar applications, and so this study was retained for analysis. The FUs used were 1 m^2 of material as well as the entire building, over a 50-year lifetime. This LCA found that as long as renewable energy was used to power the building, it had net negative emissions due to the carbon captured (GWP = -5827.05 kg CO_2 e for the entire building over 50 years).

Extracts

LCAs for extracts typically comprised a suite of products, that included alginate, laminarin, fucoidan, FDCA, levulinic acid, succinic acid, lactic acid, and single cell oils. These compounds are often used in pharmaceuticals, cosmetics, and processed foods. All of the LCAs reviewed utilized GWP as an impact category, reporting ranges from 0 to 2.87 kg CO_2 e per FU, with significant variation in individual products based on whether the energy used in processing was from renewable sources. Each LCA used a slightly different FU, which included 1 kg hydrocolloid, 1 metric ton of refined product, 1 kg dry seaweed, and 1 t feedstock. Carbon capture during cultivation was not considered in any of these LCAs.

Fertilizer

A variety of fertilizer products can be developed from macroalgae, due to their high nitrogen and phosphorus uptake, carbon content, and bioactivity. Several fertilizer products, specifically biochar, can also be produced as part of multiple product processes, such as after biofuel production (e.g., Greene, 2019; Seghetta et al., 2016). Around 15% of the carbon captured by seaweed ends up in the biochar generated during processing for biofuels in a system described by Greene, 2019, which could otherwise be considered as a waste product but can also can be used to produce fertilizer. The FUs for fertilizer products include 1 Mg dry weight (DW) of seaweed biomass produced per year, 1 metric ton of CO_2 e. removed, and 1 kiloliter of extract. GWP is utilized as a metric in one of the LCAs, with a footprint of 73.2 kg CO_2 e per 1 kiloliter of extract produced. Soil amendment with biochar seems to have significant potential for long term carbon storage, and several studies note this without including it in any metrics of LCA (Seghetta et al., 2017; Terlouw et al., 2021).

Habitat / Multispecies

Two studies consider LCA of cultivation of macroalgae as habitat, N'Yeurt et al. 2012 and Prescott 2017. N'Yeurt et al. perform a simplistic LCA on ocean afforestation that does not contain enough metrics and details to enable true assessment or comparability. Prescott 2017 reviews an integrated multitrophic aquaculture (IMTA) system, using several FUs (including 1 kg harvested fish/shellfish, and 1 ha per year cultivated) and reporting GWP (average 5217.91 kg CO_2 e per 1 ha per year of cultivated *M. pyrifera*). The LCA does not consider carbon capture, as Prescott argues that the magnitude of carbon captured was not sufficiently validated at the time of their study to include in assessment.

Multiple

Many studies consider multiple products in their LCA of a biorefinery or complete processing of macroalgae. Products co-produced include extracts, biofuels, fertilizers, and protein. It is likely that this approach yields maximum economic value of products (van Hal et al., 2014), though the carbon capture benefits are more difficult to assess. At each stage of processing, carbon can be released or transformed and without specific carbon tracking it is difficult to assess total potential with any comparability between studies.

Cultivation Only LCAs

Three LCAs consider only the cultivation of macroalgae and limited processing in the system boundary. While this is helpful for understanding hotspots to improve general climate impacts of the processes, it does not enable comparison of carbon capture permanence in the final products, which is the end goal of this paper.

A full list of LCAs reviewed for this paper with summaries of findings is available in **Appendix A**.

5.0 Results – Carbon Capture and Permanence

Table 1 provides a preliminary ranking of macroalgae products based on information available in the LCAs reviewed about the quantity and permanence of carbon captured. Note that there is significant uncertainty in this assessment and the ranking should be used only to guide further research directions and is subject to change based on additional review.

Table 1. Possible macroalgae products or uses and descriptions. Preliminary categorization of carbon capture and permanence based on review of LCAs.

Product	Usage	Quantity of CO_2 captured	Permanence
Multispecies farms / Habitat	Macroalgae can be cultivated as part of restoration projects or as a component of multispecies farms	High – the full amount of carbon captured in macroalgae is used throughout the natural life cycle	Medium / **???** – a portion of macroalgal detritus will export carbon to the deep sea sediments (geologic time scales), but not all. This is an area of active research.
Materials	Building materials Bioplastics Textiles	Medium – depending on the processing of materials for use, the amount of carbon in the final product could vary but is likely a portion of the total carbon captured in the macroalgae	High / variable – building materials, textiles and packaging (landfilled) have a life span of decades, which could qualify as permanent. Biodegradable packaging, depending on disposal practices, could have more variability in permanence
Fertilizer	N + P liquid Biochar: a carbon rich product created from pyrolysis of biomass that is durable to degradation, and can be utilized as a soil amendment for increased biomass growth and carbon return to soil	Medium / variable – biochar can be carbon-rich in many feedstocks though the proportions vary by species, and other fertilizers vary in carbon content, with higher amounts of nitrogen, phosphorus, and other nutrients	High – biochar has been shown to increase soil carbon, with a portion shown to be sequestered long term (decades to thousands of years)
Bioenergy with carbon capture and storage (BECCS)	Biomass converted to electricity at power plants outfitted with carbon capture and storage tools.	Medium – though technology is not developed, this is assumed to be promising	High – carbon captured can be stored similar to direct air capture technologies on geologic time scales
Protein	Human: available raw, dried, powdered, frozen, cooked, prepared, or as supplements Animal: as a supplement or main ingredient in feedstock for fish farms or livestock	Medium – all carbon captured in kelp can be turned into products, depending on the specific application	Low – food is consumed and carbon is returned to the system in days to months
Biofuel	Harvested macroalgae is processed and used as a biomass feedstock for fuels, including biomethane, biodiesel, bioethanol, and biogas	Medium – most LCAs consider biofuels to be at best carbon-neutral	Low – fuel is produced and consumed on the order of months – years.
Extracts	Hydrocolloids / Polysaccharides (laminarin, fucoidan, alginate, carrageenan, agar, mannitol): used in a variety of cosmetic, therapeutic, or food industry applications Oils: ingredients in specialized food or cosmetic products	**???** – depends on the total carbon contained in these extracts and the amount yielded from macroalgae harvest	**???** – depends on the shelf life of the application and final destination of the carbon contained in these products

6.0 Discussion

While this review was able to determine a preliminary ranking of macroalgae uses for carbon capture, the information available is far from comprehensive. In addition to defined knowledge gaps, several additional findings emerged through the literature review.

Many LCAs identified the electricity source used for drying as a major contributor to GWP. Switching this to renewable energy could have significant impact on net carbon emissions. Rinker et al. 2021 have identified this as feasible for kelp processing in Alaska utilizing marine energy. We recommend that this usage of marine energy be further explored in conjunction with macroalgae cultivation for various products.

Additionally, many of these studies noted that a major contributor to GWP was the use of plastic or nonrenewable materials in the construction of kelp farms or lines (e.g. (Chung et al., 2013; Koesling et al., 2021). Use of recycled materials or non-oil-based products would improve the climate impacts of macroalgae cultivation and bring the net GWP closer to neutrality or negative emissions.

While many studies did not specifically address carbon capture by macroalgae in cultivation, there still significant potential for capture that could have benefits in terms of GWP or other climate impact metrics for LCAs. Temporary storage of carbon in macroalgae may have benefits, even if it cannot be shown to have permanent sequestration (Herzog et al., 2003; Jørgensen et al., 2015). There is also methodology documented for modeling this temporary storage in LCA (Jørgensen et al., 2015) as well as opportunity for valuation of temporary storage based on permanence discounting (Kim et al., 2008). The key piece here will be to not allow temporary storage to enable continued high levels of emissions, but that emissions are reduced as well as capture increased to prevent further global impacts and irreversible change (Boettcher et al., 2021).

While LCA is a useful tool for quantifying product impacts, the studies reviewed show key limitations. Some studies did not discuss end-of-life or disposal impacts, which severely limits their use for carbon capture assessment. Many truly innovative projects are not at a phase where they able to conduct or develop LCAs (e.g., AlgiKnit and KelpBlue – textiles, SGL Carbon – carbon fiber, Checkerspot – skis and surfboards, Loliware – straws and kitchenware, Living Ink – inks and dyes). Sinking macroalgae or utilizing it as a component for other species aquaculture doesn't fit neatly into an LCA, as the product is less discrete. Clear definition of the system boundary is critical for LCA of CDR technologies (McQueen et al., 2021), especially for macroalgae as products can release the stored carbon in many different ways over a variety of timescales. In addition, a lot of the data used in LCAs is based on assumptions or indices that cannot accurately describe a site-specific process. Improvements to these data inputs (some of which are described in the next section) need to be made now so that as the technology readiness level of these aquaculture systems improve, tradeoffs in design can be accurately assessed (McQueen et al., 2021). Other tools exist that could be useful for carbon capture assessment, including technoeconomic assessment, carbon footprinting, climate tipping potential, biogenic carbon flux (and more described in Brandão et al., 2019). It is recommended that further research includes a review of the results from these tools as part of developing a framework for comprehensive assessment.

7.0 Key Knowledge Gaps: Experiments and Monitoring Needed

It is clear that knowledge gaps exist in the measurement and understanding of carbon capture in macroalgae. The Ocean Visions Roadmap for this topic (Ocean Visions, 2021) identifies several key gaps and needs, including:

- Development of tools and methods to estimate productivity, carbon capture, export, and sequestration, with both direct and remote sensing
- Methods for tracing carbon from source to deposition in high energy environments
- Net CDR benefit from a life cycle perspective
- Physiology of various cultivated species to understand growth and carbon sequestration potential
- Better understanding of how large-scale macroalgae cultivation affects the partitioning of carbon between particulate and dissolved phases, and its implications for CDR

From the literature review, the following specific gaps and potential experiments were identified that are relevant for conducting LCAs on cultivated kelp and assessing carbon capture. These gaps have been organized into research topics in Table 2. A full list of knowledge gaps identified in the literature review is available in **Appendix B**.

Table 2. Key knowledge gaps.

Topic	Key Knowledge Gaps
LCA Methods	• Establish a standard functional unit (FU) • Standardization of carbon tracking and quantification for LCAs beyond stoichiometry
Ecosystem	• Benthic and habitat impacts of cultivation, including organic loading • Impact of microplastics from seaweed farm infrastructure • Impacts on albedo and ocean temperatures from large scale cultivation • Cumulative ecosystem effects of large-scale macroalgae aquaculture • Effects of kinetic energy absorption on sediment transport and nutrient circulation • Implications of cultivation on local carbon cycling
Farm Operations	• Experiments to determine optimum farm sizes • Impacts of scale on hatchery facilities • Genetic engineering for productivity and composition
Processing	• Optimization of drying and dewatering processes • Impact of various renewable energy sources on GWP
Products	• Fertilizing potential of digestate from various macroalgal substrates for co-production with biofuel • Performance enhancements for bio packaging • Nutritional value and appropriate use of seaweed protein
Carbon Cycle	• Review of appropriate practices for application of fertilizer for maximum effectiveness • Microscopic carbon pumps and synergy with shellfish • Extent of biodegradation of various biopolymers • Temporal impacts of capture and emissions • Seasonal variation in carbon content by species • Biogeochemical impacts of sinking, drift and degradation of macroalgae • Field and long-term data for persistence of biochar carbon in soil

8.0 Conclusion

This paper provides a preliminary look at the permanence of carbon capture in macroalgae as assessed by LCAs. From this review, we find numerous methods used for carbon assessments, which makes comparison between products difficult. In addition, many LCAs take only a ‘cradle-to-gate’ approach, which ignores the end-of life aspects of production consumption or disposal, which in most cases fall within the 100-year timeframe to consider for permanence. Before macroalgae products can be accurately marketed as carbon negative or for seaweed farms to be allowed to sell carbon credits, the permanence of sequestration needs to be assessed. We have identified key knowledge gaps to be assessed through experimental research, which presents opportunities to leverage the expertise and equipment at national laboratories.

Despite lack of clarity on the exact carbon capture potential of various products, a preliminary ‘soft’ ranking of macroalgae products has been produced (Table 1). This list can provide a guide for DOE and other sponsors to determine where to invest strategically for maximum impact. With future work and updates, this list could be used by end users to provide direction for experimental farms with surplus yield to make climate-informed choices. Refinement of the top products is recommended to optimize the sequestration of carbon and create markets around this storage, while parallel research is done on the capture potential.

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Appendix A Literature Review Results

Study	Product	Species	Method	Impact Categories	Functional Unit (FU)	CO_2 and Permanence
Aitken, D., Bulboa, C., Godoy-Faundez, A., Turrion-Gomez, J. L., & Antizar-Ladislao, B. (2014). Life cycle assessment of macroalgae cultivation and processing for biofuel production. Journal of Cleaner Production, 75, 45–56. https://doi.org/10.1016/j.jclepro.2014.03.080	Biofuel: Bioethanol, biogas	*Gracilaria, M. pyrifera*	cradle-to-gate	energy return on investment, GWP_{100} (kg CO_2 eq), kg SO_2, kg PO_4 eq, ozone depletion, photochemical oxidation, toxicity.	1 MJ energy	Calculated value of captured carbon (stoichiometric carbon content of fertilizer produced) was subtracted from GWP. Assumes 1.01kg CO_2 removed for every 1kg dry weight.
Alvarado-Morales, M., Boldrin, A., Karakashev, D. B., Holdt, S. L., Angelidaki, I., & Astrup, T. (2013). Life cycle assessment of biofuel production from brown seaweed in Nordic conditions. Bioresource Technology, 129, 92–99. https://doi.org/10.1016/j.biortech.2012.11.029	Biofuel: Biogas, bioethanol + biogas	*L. digitata*	cradle-to-grave	GWP (kg CO_2 e), acidification and terrestrial eutrophication	1 metric ton of dry seaweed biomass	Assumes 1.137kg CO_2 removed for every 1kg dry weight.
Cappelli, A., Gigli, E., Romagnoli, F., Simoni, S., Blumberga, D., Palerno, M., & Guerriero, E. (2015). Co-digestion of Macroalgae for Biogas Production: An LCA-based Environmental Evaluation. Energy Procedia, 72, 3–10. https://doi.org/10.1016/j.egypro.2015.06.002	Biofuel: biogas	*Ulva*	cradle-to-grave	respiratory inorganics, climate change, ecotoxicity, acidification/eutrophication, land use, minerals	1 m^3 of biogas	Addresses avoided emissions. Carbon capture also considered within cultivation process.
Czyrnek-Delêtre, M. M., Rocca, S., Agostini, A., Giuntoli, J., & Murphy, J. D. (2017). Life cycle assessment of seaweed biomethane, generated from seaweed sourced from integrated multi-trophic aquaculture in temperate oceanic climates. Applied Energy, 196, 34–50. https://doi.org/10.1016/j.apenergy.2017.03.129	Biofuel: biomethane	*L. digitata*	cradle-to-grave	climate change (GWP), acidification, and terrestrial, marine and freshwater eutrophication	1 MJ compressed biomethane km driven in a vehicle under specific conditions	Optimized system generates 40.6 g CO_2 e, a 70% savings from gasoline use. Carbon capture not considered in cultivation.

Study	Product	Species	Method	Impact Categories	Functional Unit (FU)	CO_2 and Permanence
Ertem, F. C., Neubauer, P., & Junne, S. (2017). Environmental life cycle assessment of biogas production from marine macroalgal feedstock for the substitution of energy crops. Journal of Cleaner Production, 140, 977–985. https://doi.org/10.1016/j.jclepro.2016.08.041	Biofuel: biogas	Mix of 20% brown and 80% red	cradle-to-gate	GWP, acidification, eutrophication, and land transformation	1 kg feedstock 1 MJ energy	The combustion of biogas (biomethan e) is considered carbon neutral, such that the CO_2 captured in photosynthesis is released back into the atmosphere with no net addition of carbon.
Fry, J. M., Joyce, P. J., & Aumonier, S. (2012). Carbon footprint of seaweed as a biofuel [Marine Estate Research Report]. Environmental Resources Management Limited.	Biofuel: biomethane, bioethanol	*S. latissima, L. hyperbore a*	cradle-to-grave	carbon footprint (kg CO_2e)	1 MJ of fuel	Assumes 1.01 kg CO_2 removed for every kg dry weight.
Giwa, A. (2017). Comparative cradle-to-grave life cycle assessment of biogas production from marine algae and cattle manure biorefineries. Bioresource Technology, 244, 1470–1479. https://doi.org/10.1016/j.biortech.2017.05.143	Biofuel: biogas	*Ulva*	cradle-to-grave	carcinogens, respiratory organics, respiratory inorganics, climate change, radiation, ozone layer, ecotoxicity, acidification and eutrophication, land use, minerals, and fossil fuels	1 GJ of biogas per year	The impact of the transportation of materials required for on-land pond construction and macroalgae cultivation outweighs the environmental gains attributed to the CO_2 sequestration by macroalgae.
Greene, J. M. (2019). Techno-economic and life cycle assessment of a novel offshore macroalgae biorefinery [Master's Thesis, Colorado State University]. https://mountainscholar.org/handle/10217/197347	Multiple: diesel, N & P fertilizer	*N. luetkeana, S. latissima*	cradle-to-grave	GWP_{100} (transportation emissions, electricity emissions, HTL emissions, nutrient production)	1MJ of fuel	Of the carbon captured during macroalgal growth, about 85% (68.8 g CO_2 e) ends up in the fuel and the remaining 15% (11.79 g CO_2 e) ends up in the biochar generated.

Study	Product	Species	Method	Impact Categories	Functional Unit (FU)	CO_2 and Permanence
Greene, J. M., Gulden, J., Wood, G., Huesemann, M., & Quinn, J. C. (2020). Techno-economic analysis and global warming potential of a novel offshore macroalgae biorefinery. Algal Research, 51, 102032. https://doi.org/10.1016/j.algal.2020.102032	Multiple: diesel, naphtha, biochar, N + P fertilizers	*N. luetkeana, S. latissima*	cradle-to-grave	GWP_{100} (transportation emissions, electricity emissions, HTL emissions, nutrient production)	1 MJ of fuel	The global warming potential analysis shows net greenhouse gas emissions ranging from 14 to 29 g CO_2 e.
Halfdanarson, J., Koesling, M., Kvadsheim, N. P., Emblemsvåg, J., & Rebours, C. (2019). Configuring the Future Norwegian Macroalgae Industry Using Life Cycle Analysis. In F. Ameri, K. E. Stecke, G. von Cieminski, & D. Kiritsis (Eds.), Advances in Production Management Systems. Towards Smart Production Management Systems (pp. 127–134). Springer International Publishing. https://doi.org/10.1007/978-3-030-29996-5_15	Protein: fish feed	*S. latissima*	cradle-to-gate	GWP	1 ton protein concentrate	Does not include carbon capture. GWP decreases with increasing farm size.
Helmes, R. J. K., López-Contreras, A. M., Benoit, M., Abreu, H., Maguire, J., Moejes, F., & Burg, S. W. K. van den. (2018). Environmental Impacts of Experimental Production of Lactic Acid for Bioplastics from Ulva spp. Sustainability, 10(7), 2462. https://doi.org/10.3390/su10072462	Materials: bioplastics / lactic acid	*Ulva*	cradle-to-gate	climate change (GWP), land use, marine eutrophication	1 kg purified lactic acid and its coproducts	Carbon captured in the end product is subtracted as a credit of 1.46 kg CO_2 e (net GWP ranges from 95 – 513 kg CO_2 e). Assumes that if 1 kg of bioplastics degrade at the end of its life and releases its carbon to the atmosphere, another kg of bioplastics is produced elsewhere that stores the carbon from its biomass feedstock.
Jung, K. A., Lim, S., & Park, J. M. (2013). Life cycle global warming potential assessment of seaweed-based bioethanol. The 6th International Conference on Life Cycle Management in Gothenburg 2013, Gothenburg.	Biofuel: bioethanol	*L. japonica*	cradle-to-gate	GWP	1000 L bioethanol	Not addressed.

Study	Product	Species	Method	Impact Categories	Functional Unit (FU)	CO_2 and Permanence
Jung, K. A., Lim, S.-R., Kim, Y., & Park, J. M. (2017). Opportunity and challenge of seaweed bioethanol based on life cycle CO2 assessment. Environmental Progress & Sustainable Energy, 36(1), 200–207. https://doi.org/10.1002/ep.12446	Biofuel: bioethanol	*L. japonica*	cradle-to-grave	GWP	1000 L bioethanol	Soil carbon sequestration considered a negative value, incorporated into net GWP for land based products, but no carbon capture considered for seaweed.
Kakadellis, S., & Harris, Z. M. (2020). Don't scrap the waste: The need for broader system boundaries in bioplastic food packaging life-cycle assessment – A critical review. Journal of Cleaner Production, 274, 122831. https://doi.org/10.1016/j.jclepro.2020.122831	Materials: bioplastics	Generic	cradle-to-grave	global warming potential (GWP), non-renewable energy use, acidification potential, land use and water use	1 kg of packaging polymer	GWP values ranging from 0.70 to 11.02 kg CO_2 e. Producing bioplastics with renewable energy could reduce emissions to carbon neutral (0 kg CO_2 e). Carbon capture not considered in cultivation.
Koesling, M., Kvadsheim, N. P., Halfdanarson, J., Emblemsvåg, J., & Rebours, C. (2021). Environmental impacts of protein-production from farmed seaweed: Comparison of possible scenarios in Norway. Journal of Cleaner Production, 307, 127301. https://doi.org/10.1016/j.jclepro.2021.127301	Protein: salmon farm feed	*S. latissima*	cradle-to-gate	GWP_{100}, abiotic depletion energy, ozone layer depletion potential, acidificat ion potential, eutrophication potential, photochemical ozone creation potential, and abiotic depletion elements	1 kg crude protein	GWP varied from 2 kg to 142 kg CO_2 e.

Study	Product	Species	Method	Impact Categories	Functional Unit (FU)	CO_2 and Permanence
KTH Royal Institute of Technology, Sweden, Thomas, J.-B., Potting, J., EnviroSpotting, The Netherlands, KTH Royal Institute of Technology, Sweden, Gröndahl, F., & KTH Royal Institute of Technology, Sweden. (2021). Environmental impacts of seaweed cultivation: Kelp farming and preservation. In Cornell University, USA & X. G. Lei (Eds.), Burleigh Dodds Series in Agricultural Science. Burleigh Dodds Science Publishing. https://doi.org/10.19103/AS.2021.0091.11	Process Only: processed / preserved seaweed	*S. latissima*	cradle-to-gate	abiotic depletion, acidification, eutrophication, climate impact (GWP_{100}), ozone layer depletion, human toxicity, fresh water ecotoxicity, marine ecotoxicity, terrestrial ecotoxicity and photochemical oxidation, Cumulative Energy Demand from non-renewable and renewable sources.	1 ton freshly harvested kelp	Carbon capture from cultivation included in GWP. Study notes that if processing of kelp were included in LCA, the carbon would be released upon product consumption.
Langlois, J., Fréon, P., Delgenès, J.-P., Steyer, J.-P., & Helias, A. (2012, October 1). Life cycle assessment of alginate production. 8. International Conference on LCA in the Agri-Food Sector. https://hal.inrae.fr/hal-02749980	Extracts: phycocolloid - alginate	*S. latissima*	cradle-to-gate	GWP	1 kg hydrocolloid	Carbon capture not considered in cultivation.
Langlois, J., Sassi, J.-F., Jard, G., Steyer, J.-P., Delgenes, J.-P., & Hélias, A. (2012). Life cycle assessment of biomethane from offshore-cultivated seaweed. Biofuels, Bioproducts and Biorefining, 6(4), 387–404. https://doi.org/10.1002/bbb.1330	Biofuel: biomethane	*S. latissima*	cradle-to-grave	climate change, ozone depletion, human toxicity, photochemical oxidant formation, particulate matter formation, ionizing radiation, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, agricultural land occupation, urban land occupation, natural land transformation, water depletion, metal depletion, fossil depletion	1 km trip with a gas-powered car	Net carbon capture assumed to be zero due to release when biomethane was combusted.
Leceta, I., Etxabide, A., Cabezudo, S., de la Caba, K., & Guerrero, P. (2014). Bio-based films prepared with by-products and wastes: Environmental assessment. Journal of Cleaner Production, 64, 218–227. https://doi.org/10.1016/j.jclepro.2013.07.054	Materials: biofilms for packaging	*G. sesquipedale* (red macroalgae)	cradle-to-grave	carcinogens, respiratory organics, respiratory inorganics, climate change, radiation, ozone layer, ecotoxicity, acidification/eutrophication, land use, minerals and fossil fuels	$1m^2$ of film	Carbon capture not considered. Seaweeds are collected on beach rather than cultivated.

Study	Product	Species	Method	Impact Categories	Functional Unit (FU)	CO_2 and Permanence
Melara, A. J., Singh, U., & Colosi, L. M. (2020). Is aquatic bioenergy with carbon capture and storage a sustainable negative emission technology? Insights from a spatially explicit environmental life-cycle assessment. Energy Conversion and Management, 224, 113300. https://doi.org/10.1016/j.enconman.2020.113300	Biofuel: BECCS	*S. latissima, L. digitata, Sargassum*, and *M. pyrifera*	cradle-to-grave	energy return on investment, net GWP (biogenic carbon efficiency, carbon return on investment, energy efficiency of net carbon sequestration)	annual power demand within the region bounded by a 300-mile radius around potential geological storage sites	Assumes all injected carbon captured is permanently sequestered, but landfilled digestate releases 50% of carbon to methane/CO_2 in the atmosphere.
N'Yeurt, A. de R., Chynoweth, D. P., Capron, M. E., Stewart, J. R., & Hasan, M. A. (2012). Negative carbon via Ocean Afforestation. Process Safety and Environmental Protection, 90(6), 467–474. https://doi.org/10.1016/j.psep.2012.10.008	Multiple: kelp forest, biofuel, habitat	Generic	cradle-to-gate	CO_2 emissions	kWH/Mg of biocarbon	Assumes 19 billion tons of CO_2 per year can be stored directly from biogas production. This simplistic LCA has many additional assumptions.
Ögmundarson, Ó., Sukumara, S., Laurent, A., & Fantke, P. (2020). Environmental hotspots of lactic acid production systems. GCB Bioenergy, 12(1), 19–38. https://doi.org/10.1111/gcbb.12652	Materials: lactic acid (biochemical for packaging)	*Laminaria spp.*	cradle-to-grave	GWP, stratospheric ozone depletion, ionizing radiation, ozone formation, human toxicity, fine particulate matter impacts, tropospheric ozone formation, acidification, eutrophication, ecotoxicity, land-use, resources depletion, and water consumption	1 kg lactic acid	Assumes 0 carbon is permanently sequestered. GWP is 11 kg with drying, 5.7 without.
Parsons, S., Allen, M. J., Abeln, F., McManus, M., & Chuck, C. J. (2019). Sustainability and life cycle assessment (LCA) of macroalgae-derived single cell oils. Journal of Cleaner Production, 232, 1272–1281. https://doi.org/10.1016/j.jclepro.2019.05.315	Extracts: single cell oils	*S. latissima*	cradle-to-gate	climate change (kg CO_2 eq), freshwater ecotoxicity, freshwater eutrophication, human toxicity, marine ecotoxicity, marine eutrophication, terrestrial ecotoxicity, terrestrial acidification, and water depletion	1 metric ton of single cell oils produced	Climate change impact for process determined to be between 2.5 and 9.9 kg CO_2 e. Carbon capture not considered in cultivation.

Study	Product	Species	Method	Impact Categories	Functional Unit (FU)	CO_2 and Permanence
Philis, G., Gracey, E. O., Gansel, L. C., Fet, A. M., & Rebours, C. (2018). Comparing the primary energy and phosphorus consumption of soybean and seaweed-based aquafeed proteins – A material and substance flow analysis. Journal of Cleaner Production, 200, 1142–1153. https://doi.org/10.1016/j.jclepro.2018.07.247	Protein: aquafeed	*S. latissima*	cradle-to-gate	cumulative primary energy demand	0.61 t of pure protein	Carbon capture not considered, though nitrogen and phosphorus uptake are.
Prescott, S. G. (2017). Exploring the Sustainability of Open-Water Marine, Integrated Multi-Trophic Aquaculture, Using Life-Cycle Assessment. http://dspace.stir.ac.uk/handle/1893/28269	IMTA/ Habitat	*M. pyrifera*	cradle-to-grave	abiotic depletion, GWP_{100} (kg CO_2 eq), ozone layer depletion, human toxicity, freshwater ecotoxicity, marine ecotoxicology, terrestrial ecotoxicology, photochemical ozone creation, acidification, eutrophication	1 kg wet weight	Carbon capture not considered in cultivation, Notes that carbon sequestration isn't validated enough to be included in a realistic assessment.
Sadhukhan, J., Gadkari, S., Martinez-Hernandez, E., Ng, K. S., Shemfe, M., Torres-Garcia, E., & Lynch, J. (2019). Novel macroalgae (seaweed) biorefinery systems for integrated chemical, protein, salt, nutrient and mineral extractions and environmental protection by green synthesis and life cycle sustainability assessments. Green Chemistry, 21(10), 2635–2655. https://doi.org/10.1039/C9GC00607A	Extracts: FDCA, levulinic acid, succinic acid, lactic acid	*Sargassum, sea lettuce, euchemia*	cradle-to-gate	fossil fuel depletion, global warming and freshwater aquatic ecotoxicity potentials	1 kg dry seaweed	For an integrated biorefinery, GWP is 0.05 kg CO_2 e for protein, sugar and inorganics and 0 kg CO_2 e for levulinic acid, FDCA, succinic acid and lactic acid. These values are calculated based on comparison to meat, not including carbon capture in cultivation.

Study	Product	Species	Method	Impact Categories	Functional Unit (FU)	CO_2 and Permanence
Seghetta, M., Hou, X., Bastianoni, S., Bjerre, A.-B., & Thomsen, M. (2016). Life cycle assessment of macroalgal biorefinery for the production of ethanol, proteins and fertilizers – A step towards a regenerative bioeconomy. Journal of Cleaner Production, 137, 1158–1169. https://doi.org/10.1016/j.jclepro.2016.07.195	Multiple: ethanol, protein, fertilizer	*L. digitata*	cradle-to-grave	climate change (kg CO_2 eq), cumulative energy demand (MJ), marine eutrophication (N and P), human toxicity	1 ha of sea cultivated	GWP is reported as -100 kg CO_2 e. When applying biofertilizers, 10% of the carbon is considered undecomposed after 100 years, increasing the carbon stored in soil and causing a net reduction in atmospheric CO_2..
Seghetta, M., Romeo, D., D'Este, M., Alvarado-Morales, M., Angelidaki, I., Bastianoni, S., & Thomsen, M. (2017). Seaweed as innovative feedstock for energy and feed – Evaluating the impacts through a Life Cycle Assessment. Journal of Cleaner Production, 150, 1–15. https://doi.org/10.1016/j.jclepro.2017.02.022	Multiple: biogas (methane), fish feed ingrediants, fertilizer	*L. digitata, S. latissima*	cradle-to-grave	climate change (kg CO_2 eq), cumulative energy demand (MJ), marine eutrophication (N and P), human toxicity	1 ha of sea cultivated	Includes carbon capture as a credit in protein production (25,720 and 48,762 Mg CO_2 e) and in avoided emissions for biogas (1253, 869, 2832 Mg CO_2 eq).
Seghetta, M., Tørring, D., Bruhn, A., & Thomsen, M. (2016). Bioextraction potential of seaweed in Denmark—An instrument for circular nutrient management. Science of The Total Environment, 563–564, 513–529. https://doi.org/10.1016/j.scitotenv.2016.04.010	Fertilizer	*S. latissima*	cradle-to-cradle	freshwater and marine eutrophication	1 Mg dry weight	Carbon capture not included in analysis, more emphasis given to nitrogen and phosphorus.
Shushpanova, D. V., & Kapralova, D. O. (2021). Life-Cycle Assessment of Kelp in Biofuel Production. IOP Conference Series: Materials Science and Engineering, 1079(7), 072023. https://doi.org/10.1088/1757-899X/1079/7/072023	Biofuel: biogas, bioethanol and biodiesel	*S. latissima, L. digitata, L. japonica*	cradle-to-gate	NA	NA	Overview of LCA presents little details. Carbon capture not considered.
Slegers, P. M., Helmes, R. J. K., Draisma, M., Broekema, R., Vlottes, M., & van den Burg, S. W. K. (2021). Environmental impact and nutritional value of food products using the seaweed Saccharina latissima. Journal of Cleaner Production, 319, 128689. https://doi.org/10.1016/j.jclepro.2021.128689	Protein: burger, salt	*S. latissima*	cradle-to-grave	GWP, freshwater eutrophication potential, land use, fossil resource scarcity, water consumption	1 kg edible product	Carbon capture not considered in cultivation. Note that human consumption is not considered despite claim of cradle-to-grave.

Study	Product	Species	Method	Impact Categories	Functional Unit (FU)	CO_2 and Permanence
Taelman, S. E., Champenois, J., Edwards, M. D., De Meester, S., & Dewulf, J. (2015). Comparative environmental life cycle assessment of two seaweed cultivation systems in North West Europe with a focus on quantifying sea surface occupation. Algal Research, 11, 173–183. https://doi.org/10.1016/j.algal.2015.06.018	Process Only	*S. latissima*	cradle-to-gate	biotic renewables, atmospheric resources, fossil fuels, land resources, marine resources, metal ores, minerals, nuclear energy and water	1 MJ ex of dry seaweed	Carbon capture not considered in cultivation. Carbon not included in impact categories.
Terlouw, T., Bauer, C., Rosa, L., & Mazzotti, M. (2021). Life cycle assessment of carbon dioxide removal technologies: A critical review. Energy & Environmental Science, 14(4), 1701–1721. https://doi.org/10.1039/D0EE03757E	Multiple: biochar, biofuel	Generic	cradle-to-grave	GWP	1 metric ton of CO_2 removed	Soil amendment with biochar seems to offer most potential in terms of CO_2 removal and storage.
Thomas, J.-B. E., Sodré Ribeiro, M., Potting, J., Cervin, G., Nylund, G. M., Olsson, J., Albers, E., Undeland, I., Pavia, H., & Gröndahl, F. (2021). A comparative environmental life cycle assessment of hatchery, cultivation, and preservation of the kelp Saccharina latissima. ICES Journal of Marine Science, 78(1), 451–467. https://doi.org/10.1093/icesjms/fsaa112	Process Only	*S. latissima*	cradle-to-gate	abiotic depletion, acidification, eutrophication, global warming potential over 100 years, ozone layer depletion, human toxicity, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity and photochemical oxidation. Also includes cumulative energy demand (renewable and non-renewable)	1 metric ton fresh kelp	The capture of carbon is based on the composition of *S. latissima* (carbon: 26.2% of dry matter), converted to CO_2 e and counted as credits toward GWP.
Tonini, D., Hamelin, L., Alvarado-Morales, M., & Astrup, T. F. (2016). GHG emission factors for bioelectricity, biomethane, and bioethanol quantified for 24 biomass substrates with consequential life-cycle assessment. Bioresource Technology, 208, 123–133. https://doi.org/10.1016/j.biortech.2016.02.052	Biofuel: biomethane, bio electricity, bioethanol	*L. digitata*	cradle-to-gate	GHG Emissions (gCO_2 eq/MJ or kWh), land use change	1 kw bioelectricity 1 MJ fuel	Seaweed has GHG savings but doesn't appear to reflect carbon capture. GWP = 51 g CO_2 e
van Oirschot, R., Thomas, J.-B. E., Gröndahl, F., Fortuin, K. P. J., Brandenburg, W., & Potting, J. (2017a). Explorative environmental life cycle assessment for system design of seaweed cultivation and drying. Algal Research, 27, 43–54. https://doi.org/10.1016/j.algal.2017.07.025	Protein: protein	*S. latissima*	cradle-to-gate	ozone layer depletion, human toxicity, fresh water aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, photochemical oxidation, climate change, acidification, abiotic depletion and eutrophication	1 ton protein	Carbon capture not considered in cultivation.

Study	Product	Species	Method	Impact Categories	Functional Unit (FU)	CO_2 and Permanence
Vijay Anand, K. G., Eswaran, K., & Ghosh, A. (2018). Life cycle impact assessment of a seaweed product obtained from Gracilaria edulis – A potent plant biostimulant. Journal of Cleaner Production, 170, 1621–1627. https://doi.org/10.1016/j.jclepro.2017.09.241	Fertilizer: biostimulant	*Gracilaria*	cradle-to-gate	agricultural land occupation, climate change [kg CO2 eq], fossil depletion, freshwater ecotoxicity, freshwater eutrophication, human toxicity, ionizing radiation, marine ecotoxicity, marine eutrophication, metal depletion, natural land transformation, ozone depletion, particulate matter formation, photochemical oxidant formation, terrestrial acidification, terrestrial ecotoxicity, urban land occupation, water depletion	1 m^3 extract	Carbon footprint for production of 1000 L of *Gracilaria* extract was 73.2 kg CO_2 e. Carbon capture not considered in cultivation.
Widera, B. (2014). Possible Application of Seaweed as Building Material in the Modern Seaweed House on Laesø. https://doi.org/10.13140/RG.2.1.1638.2881	Materials: buildings	*Z. marina*	cradle-to-grave	GWP100 (kg eq. CO_2), ozone depletion potential, photochemical ozone creation potential, acidification potential, eutrophication potential, non-renewable primary energy demand, renewable primary energy demand, total primary energy demand, water usage, waste production, hazardous waste production, abiotic resource depletion, excavation residues	1 m^2 building materials	With proper insulation and utilization of wind energy, the building has a negative carbon footprint (GWP = -5827.05 kg CO2 e total over 50 years).

Study	Product	Species	Method	Impact Categories	Functional Unit (FU)	CO_2 and Permanence
Zhang, X., Border, A., Goosen, N., & Thomsen, M. (2021). Environmental life cycle assessment of cascade valorisation strategies of South African macroalga Ecklonia maxima using green extraction technologies. Algal Research, 58, 102348. https://doi.org/10.1016/j.algal.2021.102348	Extracts: alginate, laminarin, fucoidan	*E. maxima*	harbor-to-gate	GWP, marine eutrophication, mineral resource scarcity, water consumption, blue water footprint	1 t feedstock dry weight	The results showed doubled carbon footprints in both processing systems are higher than the reference system, being 25,665, 13,530, and 5,188 kg CO_2 e. Carbon capture not considered in cultivation, though the study includes avoided emissions from cows eating it as food instead.

Appendix B Knowledge Gaps from Literature Review

The list below provides knowledge gaps that were identified in each of the LCAs in the literature review:

- True biofuel yield from M. pyrifera (Aitken et al., 2014)
- Fertilizing potential of digestate from various macroalgal substrates (in conjunction with biofuel) (Czyrnek-Delêtre et al., 2017)
- Appropriate practices for application of fertilizer for maximum effectiveness (Czyrnek-Delêtre et al., 2017)
- Impacts of regional factors for harvest metrics (Ertem et al., 2017)
- Optimization of pre-treatment for fertilizer production from digestate (Ertem et al., 2017)
- Impacts of scaling up hatchery facilities to extra large biofuel farms (Greene, 2019)
- Integration of carbon fiber in a free-floating system (Greene, 2019)
- Development of bioadhesive to eliminate nylon twine from system (Greene, 2019)
- Quantifying exchanges between seaweed and the sea, specifically toxicity and phosphorus (Helmes et al., 2018)
- Benthic and habitat impacts of cultivation (Helmes et al., 2018; van Oirschot et al., 2017)
- Genetic engineering for seaweed productivity and composition (Jung et al., 2013)
- Extent of biodegradation of various biopolymers (Kakadellis & Harris, 2020)
- Functional performance enhancements for bio packaging (Kakadellis & Harris, 2020)
- Nutritional value of seaweed protein (Koesling et al., 2021)
- Impact of microplastics from seaweed farm infrastructure (Koesling et al., 2021)
- More LCAs to guide the design principles of cultivation systems, preservation and processing methods as new commercial enterprises grow and collect data (KTH Royal Institute of Technology, Sweden et al., 2021)
- Effects of sustained areal yield on transport and system metrics (Melara et al., 2020)
- Impacts on albedo and ocean temperatures from large scale cultivation (N‘Yeurt et al., 2012)
- Cumulative ecosystem effects (Parsons et al., 2019)
- Suitability of raw seaweed as an ingredient for fish nutrition (Philis et al., 2018)
- Impact of organic loading to the benthos, specifically for IMTA (Prescott, 2017)
- Human toxicity from finfish aquaculture based on seaweed ingredients (Seghetta et al., 2017)
- Optimization of drying and dewatering processes (Seghetta et al., 2017)
- Temporal impacts of capture and emissions (Terlouw et al., 2021)
- Seasonal variation in nitrogen, phosphorus, and carbon content (Thomas et al., 2021)

A few other review papers identify additional specific gaps and data needs:

- (Campbell et al., 2019)
    - Trophic changes due to changes in light availability
    - Site specific nitrogen mass balances
    - Implications of cultivation on local carbon cycling
    - Contribution of cultivated losses to carbon sequestration
    - Effects of kinetic energy absorption on sediment transport and nutrient circulation
    - Biogeochemical effects of drift and decomposition

- Impact of sinking and degradation of macroalgae (Pedersen et al., 2021; Wernberg & Filbee-Dexter, 2018)
- Microscopic carbon pumps and synergy with shellfish (Zhang et al., 2017)
- Trophic cascades (Wilmers et al., 2012)
- Field and long-term data for persistence of biochar carbon in soil (Wang et al., 2016)

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