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OVERVIEW

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Seaweed as climate mitigation solution: Categorizing and reflecting on four climate mitigation pathways

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Abstract

Global concerns about climate change were once again expressed at the COP27 in Sharm El-Sheikh. Seaweed is frequently presented as a solution for climate mitigation. For a proper appraisal of its contribution to mitigating climate change, it is necessary to distinguish between, and critically scrutinize, the various pathways seaweed-based climate mitigations can take. This article identifies four different climate mitigation pathways and critically reflects on each. First, carbon sequestration, occurring when grown seaweed is left in the seas or, second, purposefully sunk. Third, carbon emission reduction, resulting when seaweed-based products replace products with a higher carbon footprint, either fossil based products or other organic material. Fourth, carbon emission avoidance, taking place when seaweed products are used to avoid greenhouse gas emissions in other production processes. Each of these pathways requires specific methods to quantify their magnitude and comes with critical questions to ask. The sequestration pathway requires monitoring of net carbon production and the amount of carbon that is eventually exported to the deep sea. Pathways 3 and 4 require Life Cycle Assessment and/or Carbon Footprint with system boundaries set to include the production system itself and installation thereof. We propose an unequivocal categorization in a belief that confusion on the benefits of seaweed will eventually impede development of seaweed-based solutions.

This article is categorized under:

The Carbon Economy and Climate Mitigation > Benefits of Mitigation

KEYWORDS

blue carbon, carbon footprint, carbon sequestration, climate, LCA, mitigation, seaweed, trade-offs

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1 | INTRODUCTION

Global concerns about climate change have been once again expressed at the global climate conference COP27 in Sharm El-Sheik, 7 years after agreeing on the Paris Climate Agreement ambitions to limit global warming to 1.5°C. It is the first IPCC report to officially declare climate change human induced (IPCC, 2021). The world is in need of solutions that stabilize or reduce the atmospheric CO_2 concentration through emissions reduction and proactive removal of CO_2 from the air.

The United Nations Global Compact argues that seaweed (the common name to marine macroalgae, classified according to their pigmentation into brown (Phaeophyta), red (Rhodophyta), and green (Chlorophyta) seaweeds (Chan et al., 2006)) is a "climate champion" unknown to many and that "it has significant potential to help build the safe, sustainable and prosperous future we want".[1] Duarte (2022) argued that seaweed aquaculture lead to direct benefits in advancing a number of the Sustainable Development Goals (SDG), such as SDG 2 (Zero hunger, aiming at ending hunger, achieving food security and improved nutrition and promote sustainable agriculture), SDG 3 (Good health and well-being, aiming at ensuring healthy lives and promoting well-being for all at all ages), SDG 7 (affordable and clean energy, aiming at ensuring access, to affordable, reliable, sustainable, and modern energy for all), SDG 13 (climate action, aiming at taking urgent action to combat climate change and its impacts), and SDG 14 (life below water, aiming at conserving and sustainably using the oceans, seas and marine resources for sustainable development) (Duarte et al., 2021). Various scientific projects and foundations investigate and promote the use of seaweed for mitigating climate change. Oceans2050 launched a global study that will help restore abundance to the world's ocean while advancing climate restoration through seaweed aquaculture (Duarte, 2022), and in a preprint version, results are shown on the carbon sequestration potential of seaweed below the farms in the sediments (Duarte et al., 2023). Offshore marine aquaculture is promoted to reverse climate change with huge hovering seaweed farms that are fueled by wave powered upwelling.[2] North Sea Farm 1 is financially supported with reference to the argument claim that seaweed has potential to help tackle climate change.[3] To learn and combine forces network organization have been created mapping ongoing projects, providing a database of seaweed organizations or bringing together organization from the whole seaweed value chain. This enthusiasm about seaweed as climate solution has triggered debates on the inclusion of seaweed in carbon offsetting schemes and Seaweed Certificates are on the market.

Overlooking these initiatives and visions, it should not go unnoticed that many different activities are captured under the umbrella term "climate change mitigation". The online weekly periodical *Time* writes: "Seaweed can play a huge role in fighting climate change by absorbing carbon emissions, regenerating marine ecosystems, creating biofuel and renewable plastics as well as generating marine protein".[4] The magazine New Scientist argues that "large-scale seaweed farms could clean up Earth's oceans, restoring biodiversity and increasing the productivity of aquaculture. They could remove carbon dioxide from the air and help curb the emission of other greenhouse gases."[5]

Both quotes show lump together the different ways through which seaweed aquaculture and use can help fight climate change. The inaccurate use of terminology, not distinguishing between aquaculture and ecosystem restoration and mixing up of short- and long-term carbon cycles fuels confusion and might create unrealistic future expectations of seaweed. Costa-Pierce and Chopin (2021) support this and argue it is important to not promise the moon and denounce claims of miracle cures. Troell et al. (2022) critically challenge those arguing that a carbon sink function exists simultaneously with use of seaweeds in products. This article aims to contribute to the debate on the role of seaweed in carbon mitigation and offsetting. It identifies, describes, and analyzes different pathways for climate mitigation by cultivation and use of seaweed. This includes (i) providing definitions that allow one to distinguish different pathways for climate mitigation, (ii) identifying methods that can be used to quantify the contribution to climate mitigation, and (iii) formulating critical questions to consider before concluding on the feasibility of seaweed as climate solution. The following sub-objectives are identified:

- What are the possible pathways via which seaweed can contribute to climate change mitigation?
- What terminology can be used to discuss these pathways unequivocally?
- Which methodologies can be used to quantify the contribution to climate change mitigation?
- What are the critical questions related to these mitigation pathways?

This article contributes to a larger debate on seaweeds potential contribution to climate change mitigation. Various recent studies published aim to quantify how much carbon is, and how much is not, sequestered in the deep sea (Duarte et al., 2017; Froehlich et al., 2019; Gao et al., 2022; Yong et al., 2022). This article's contribution instead lies in the identification of, and critical look into, the various pathways. This article does not aim to detect true and false claims and to discredit seaweed's potential, but rather puts the spotlight on various ways in which seaweed can contribute to climate change mitigation. It is acknowledged that in European seaweed cultivation is in its infancy (Barbier et al., 2019).

Also, the European market is still small compared to Asia but an increase in demand for algae and algae-based products is expected (Araújo et al., 2021; European Comission, 2022), among other driven by the development of new products (Blikra et al., 2021; Morais et al., 2020; Stirk et al., 2020) and changing consumer preferences (Li et al., 2021; Onwezen et al., 2021). The article does not deal with the climate impact of natural kelp forests, a topic discussed in various publications (Filbee-Dexter & Wernberg, 2020; Howard et al., 2017).

2 | FOUR SEAWEED CLIMATE MITIGATION PATHWAYS

Four pathways for climate change mitigation through seaweed can be identified, in line with categorizations provided in earlier discussion on voluntary carbon offsets (Ramseur, 2009) that distinguished between sequestration (following the IPCC, defined as removal from the atmosphere for at least 100 years,[6] reduction and avoidance. After discussing these pathways, this article provides a critical reflection on each of them.

2.1 | Pathway 1: Grow seaweed specifically for carbon sequestration

The first pathway encompasses those efforts where seaweed is grown and subsequently left in the water, analogous to the planting of trees on land. Both contribute to carbon sequestration, defined as "the process of storing carbon in a carbon pool."[7] The capacity for seaweed to draw down CO_2 and to fix it into organic matter, has been demonstrated (Chung et al., 2011, 2013; N'Yeurt et al., 2012). Based on assumptions from wild seaweed it was shown that the carbon capture potential of cultivated seaweed is at least as high as that of terrestrial farmed crops (Laurens et al., 2020).

It has taken a while to recognize that seaweed can sequester carbon as it was thought that the large majority of seaweed production is either decomposed in the ocean (Krumhansl & Scheibling, 2012), or consumed and therefore has a quick turnover rate (Duarte et al., 2013; Howard et al., 2017). Several researchers have challenged this view (Hill et al., 2015; Moreira & Pires, 2016; Trevathan-Tackett et al., 2015), suggesting that, dependent on location-specific oceanographic processes, part of the of seaweed is buried by being transported to other parts of the ocean. Evidence is provided that seaweeds are globally relevant contributors to oceanic carbon sinks, acting as carbon-donors (Hill et al., 2015; Krause-Jensen & Duarte, 2016; Raven, 2017; Trevathan-Tackett et al., 2015; Yong et al., 2022). Krause-Jensen and Duarte (2016) estimated that seaweed could sequester up to 173 TgC per year (with a range between 61 and 268 TgC $year^{-1}$) globally, which is about 11% of seaweed global net C-production at the time. Based on these calculations, seaweed may be supporting higher global C burial rates than seagrass, tidal marshes, and mangroves combined (Macreadie et al., 2019; Wu et al., 2020). More studies are needed to challenge or support these numbers and possibly reduce the uncertainty propagation analysis used in their methods.

It is necessary to differentiate between Particulate Organic Carbon (POC) and Dissolved Organic Carbon (DOC) (Kharbush et al., 2020) and the way they can contribute to storing carbon. For the first pathway, it is important to acknowledge that POC and DOC from seaweed can enter both carbon cycles: the long-term carbon cycle and the short-term carbon cycle. When entering the long-term carbon cycle, carbon is removed from the cycle relevant to most life on earth (recalcitrant DOC), versus, when entering the short-term cycle, carbon atoms are being reused by organisms and then released into the atmosphere again. Only recalcitrant DOC can be sequestered for a long time in the ocean, being resistant to microbial degradation (Li et al., 2022). Remineralization rate and tracing the fate of carbon in dynamic coastal waters are examples of unknown variables, that still need more attention to solve the carbon sequestration potential equation (Hurd et al., 2022). Even when macroalgae are farmed for human use, and thus harvested, there can still be recalcitrant carbon from POC and DOC released and broken off during its growth and therefore considered sequestered. How much carbon this actually is, is currently studied in various research projects.[8]

2.2 | Pathway 2: Human-induced sequestration of carbon within seaweed biomass

In addition to the natural processes of sequestering carbon, where seaweed breaks of and naturally sinks to the deep sea, there are now ideas to harvest or even cultivate seaweed and artificially sink this to the deep ocean. This process is therefore enhancing the biological pump. Commercial initiatives[9] aim to capture CO_2 and store it away in the deep ocean sediment and are now testing to build offshore seaweed forests, essentially floating seaweed farms that will sink automatically when grown enough. It is based on the fact that after 3 months seaweed loses its buoyancy (Vandendriessche et al., 2007).

The "golden tide" in 2011 where exceptionally large masses of *Sargassum*, started appearing around the Caribbean, Gulf of Mexico, northern Brazil and the western coast of Africa (López-Contreras et al., 2021; Smetacek & Zingone, 2013) intensified the research on carbon sinks (Gouvêa et al., 2020). The idea behind the Sargassum Ocean Sequestration of Carbon ("SOS Carbon",[10] a patent-pending technology) is to attach "Littoral Collection Modules (LCMs) to artisanal fishing boats to collect *Sargassum* in nets which are brought to a barge. When full, the barge is towed to the deep ocean where *Sargassum* is pumped to critical depths of around ∼150–200 m depth, whereafter it continues sinking (Gray et al., 2021).

For the carbon in accumulated seaweed biomass to enter the long-term carbon cycle, the seaweed should be introduced at locations where optimal burial of seaweed biomass can take place. This way, as little biomass as possible is converted into CO_2 or degradable dissolved carbon compounds. Siegel et al. argue that the depth at which- and where the carbon would be sunk, plays a vital role in the time it stays sequestered (Siegel et al., 2021). Because ocean currents will eventually bring it back to the ocean surface. Their work aimed at finding optimal depth at which matter can stay sequestered without resurfacing too soon. In his model carbon from seaweed can be sequestered (via biological pump enhancement) on average 109 years. According to his model, carbon would stay sequestered for longer, if for instance, artificially injected at 2000 or 3000 m. Geoengineering ideas like storing seaweed in geosynthetic containers on the deep ocean seabed are also voiced (GESAMP, 2019). Discussions on these concepts need further discussion, not only from an ecological perspective, but also from an ethical one.

2.3 | Pathway 3: Low carbon footprint seaweed based products

A broad range of seaweed-based products has been developed and studied, using seaweed as an alternative feedstock biomass. This includes use of seaweed as human food, animal feed, bioplastics, and biofuel. These seaweed products are promised to come with lower greenhouse gas (GHG) emissions and therefore are a climate-friendly alternative (Lean et al., 2021). For a correct understanding of this latter claim, it helps to distinguish between those instances where seaweed-based products replace either fossil-fuel based products (such as fuel Laurens & Nelson, 2020), plastic (Carina et al., 2021; Zhang et al., 2019), etc.), or other products such as food (Boukid et al., 2021; van der Heide et al., 2021) and feed (Emblemsvåg et al., 2020; Muizelaar et al., 2021).

When seaweed-based products are used for the production of fuel, either for automobiles or aviation, fossil resource use is potentially decreased. Algae are presented as an attractive, alternative renewable source for biofuel production compared to biomass from food crops or cellulosic materials (Laurens et al., 2017; Laurens & Nelson, 2020; Rahpeyma & Raheb, 2019). Biomethane produced from seaweed is considered as a third-generation renewable gaseous fuel. The advantage of seaweed for biofuel is that it does not compete directly or indirectly for land with food, feed, or fiber production (Czyrnek-Delêtre et al., 2017). Similarly, the use of seaweed for packaging can replace fossil fuel use (Zhang et al., 2019).

Various ways to use seaweed in human food as described, including use as main ingredient or flavor agent. Seaweeds are also added for their nutritional value or to improve food color and appearance (Blikra et al., 2021; Figueroa et al., 2021). Others have studied the use of seaweeds as novel protein source, as alternative to meat or other vegetal sources (Rawiwan et al., 2022; Samarathunga et al., 2022).

2.4 | Pathway 4: Use seaweed to reduce emissions in other production processes

In this fourth pathway, GHG emission reductions are realized by adding seaweed or seaweed extracts to other production processes. The example of this that received most attention is addition of seaweed to reduce enteric CH_4 (methane) emissions from ruminants (Abbott et al., 2020; Duarte, 2017; Spillias et al., 2023) but the pathway also includes use of seaweed extract in arable farming. Livestock production is a major contributor to GHG emissions, among others because the enteric fermentation of ruminants causes CH_4 emissions. Ruminant livestock can produce 250–500 L of methane per day (Johnson & Johnson, 1995). Enteric methane emissions are the single largest source of direct GHG emissions in beef and dairy value chains and a substantial contributor to anthropogenic methane emissions globally. Dietary manipulation is one of the proposed strategies to reduce methane emissions (Haque, 2018). A meta-review conducted by Lean et al. (2021) observes that the dominant species used in experiments are *Asparagopsis taxiformis* and

Ascophyllum nodosom, although there are multiple publications that describe the use of different species present globally. Lean et al. (2021) conclude that the limited available data points to a significant and substantial reduction in methane emissions, while there is no evidence that that addition of seaweeds benefitted growth. The addition of seaweeds to animal feed also comes with some risks regarding iodine and heavy metal concentrations which could bioaccumulate. These require more research, and regulations regarding seaweeds heavy metal concentrations are not yet in place (Morais et al., 2020).

The use of seaweed-derived biostimulants (a product stimulating plant nutrition processes independently of the product's nutrient content)[11] for terrestrial agriculture has also been evaluated from a climate mitigation perspective, for example by Singh et al. (2018) who conducted field trials to demonstrate the potential of a *Kappaphycus alvarezii* seaweed based biostimulant in combination with recommended rate of synthetic fertilizers (RRFs) for sustainably enhancing sugarcane production and mitigating environmental impacts. The study advocates a paradigm shift in policy to encourage use of biostimulants in the context of mitigating adverse effects of global climate change and expecting better returns from sugarcane cultivation. The potential of biochar production with seaweed allowing for further carbon removal from the atmosphere was research as a biological carbon capture coupled with biomass production (Hughes et al., 2012).

3 | AN OVERVIEW OF PATHWAYS, METHODS, AND QUESTIONS

Table 1 below provides an overview of the four pathways. For each pathway, examples are given, the methods used to analyze climate impacts and pertinent challenges are given.

4 | CAN THE CONTRIBUTION TO CLIMATE MITIGATION BE QUANTIFIED?

For all pathways, the carbon uptake needs to be measured and quantified. This can be done by analyzing the final content of carbon in the biomass. Carbon uptake measurements usually are on harvested seaweed samples and then analyzed in a lab. If no samples can be taken, a rough estimate of 30% carbon content on a dry weight basis in cultivated seaweeds can be used (Kim et al., 2017; Laurens et al., 2020). For pathways 1 and 2, the fate of the carbon needs to be monitored (Macreadie et al., 2019) and how long it stays there (permanence). Both are complex to understand and monitor, but crucial for claiming sequestration and the challenging parts of the methodology. Studies as early as 1980 had already started looking into this via the outwelling hypothesis (Odum, 1980).

For pathway 1, a solid understanding of the fate of C originating from these seaweed systems is needed (Macreadie et al., 2019). There is evidence that some of the seaweed detritus material ends up in the deep ocean, it has been observed in the deep sea below 1000 m (Krause-Jensen & Duarte, 2016). Taking sediment core samples in the deep sea, gives insight on the amount of seaweed derived carbon and existence in the deep sea (Hidayah et al., 2022; Rose & Hemery, 2023; Santos et al., 2019), but these samples do not indicate where the carbon originated and what the ratio of sequestration per biomass would be. Ortega et al. (2019) conclude that macroalgae transport to the deep sea takes, place, based on eDNA analysis. Signals from macroalgae are found throughout the global ocean and the relative abundance of kelp DNA in particulate organic matter increases from 3000 to 4000 m (Ortega et al., 2019). Environmental DNA (eDNA) analysis can identify specific species contribution to the carbon in the sediment (Hamaguchi et al., 2022; Ortega et al., 2020), which can help with the determination of the permanence. However, with eDNA the quantity of carbon sequestered from this species cannot be determined. Geraldi recommends using multiple complementary methods to identify the source of carbon in marine sediment for example carbon and nitrogen isotopes of lipids along with eDNA (Geraldi et al., 2019), although the effect of decomposition on the stable isotope signature requires more research (Kelleway et al., 2022). Macreadie summarized in 2019, that if we want to not only measure C sequestration locally, but now recognize that it needs to be measured more globally, we also need more refined estimates of the global surface area of seaweed-dominated systems (Macreadie et al., 2019) and insight into areas suitable for seaweed cultivation (Froehlich et al., 2019). A forensic Carbon Accounting approach to assess the magnitude of CO_2 removal through seaweeds, by attributing the sequestered carbon to seaweed, is another thorough method (Hurd et al., 2022). Mixed methods and numerical modeling are used by for instance Dolliver and O'Connor (2022) or purely numerical models by Wu et al. (2023), Siegel et al. (2021), and Coleman et al. (2022), although the authors of these studies state that many uncertainties remain.

TABLE 1 Disentangling the role of seaweed in climate change mitigation.

Terminology	Specifically growing seaweed for carbon sequestration	Human-induced sequestration of carbon within seaweed biomass	Lower carbon footprint seaweed-based products	Reduce emissions in other production processes
Principle	Long term (>100 years) storage of recalcitrant DOC in the ocean, resistant to microbial degradation	Collect and sink seaweed to the deep sea	Provide climate-friendly seaweed-based alternatives to conventional products	Use seaweed to reduce GHG emissions in other processes such as terrestrial agriculture and livestock farming
Example	Installing kelp forest/ seaweed beds (Chung et al., 2013)	Sargassum ocean sequestration of carbon (Gray et al., 2021)	Bioplastics from seaweed (Helmes et al., 2018)	Reduce CH_4 emissions from ruminants (Muizelaar et al., 2021)
Possible trade offs	Negative ecosystem impacts of (large-scale) seaweed forest restoration	Net climate effect uncertain due to energy use in collection and sinking seaweed Negative ecosystem impacts of sinking	Net climate effect uncertain due to high energy use in cultivation and processing seaweed Negative ecosystem impacts of cultivation	Net climate effect uncertain due to high energy use in cultivation Negative ecosystem impacts of cultivation Impact of seaweed products on animal and plant health
Methods to consider for assessing climate impact	Biomass sampling. Monitoring of fate of total inorganic carbon and net community production	LCA and carbon footprint with system boundaries to include harvesting and sinking of seaweed Impact assessment and long-term monitoring of the deep sea ecosystem to guarantee long term storage and no disruption of natural occurring carbon sinks like methane hydrates	LCA and carbon footprint with system boundaries to include the production system and installation thereof, including comparison with conventional products	LCA and carbon footprint with system boundaries to include the production system and installation thereof

For pathways 3 and 4, it is essential to look at the full life cycle impacts (Troell et al., 2022). Life Cycle Assessment (LCA) and Carbon Footprint are well-established methods to evaluate the contribution of seaweed to climate mitigation. LCA is a holistic methodology that identifies the impact of a production system has on the environment taking into consideration all stages of product manufacturing (Seghetta & Goglio, 2020). This means, besides the production and extraction of resources, it also includes data on the transport, use, recycling, and disposal of the remaining waste (Rebitzer et al., 2004). The protocol to conduct an LCA is formalized in the ISO standard 14040:2006 and 14044:2006 and application to seaweed use is discussed (Hasselström & Thomas, 2022; Seghetta & Goglio, 2020).

5 | WHAT IS THE CARBON BALANCE OF PRODUCING AND PROCESSING SEAWEEDS?

Studies into seaweed cultivation point to the high energy demand of seaweed cultivation (IPCC, 2014). A LCA study conducted on experimental offshore seaweed cultivation concluded that the vessel used for installation of the seaweed farm was largely responsible for GHG emissions and a more efficient approach is needed (Slegers et al., 2021). Alvarado-Morales et al. (2013) studied the use of seaweed for biofuel production. A consequential life cycle assessment (LCA) and an energy analysis of seaweed-based biofuel production were carried out in Nordic conditions to document and improve the sustainability of the process. In both scenarios the brown seaweed species *Laminaria digitata* was used, either for biogas production or for bioethanol + biogas production. Potential environmental impact categories under investigation were global warming, acidification and terrestrial eutrophication. The production of seaweed was identified to be the most energy intensive step.

LCA and Carbon Footprint can be used to evaluate GHG balances. The reported high GHG emissions of seaweed cultivation means that system boundaries, referring to goal and scope needed for an LCA study, should include the production and installation of the cultivation system, as well as the greenhouse gas emissions associated with the transport, storage, processing and distribution of seaweed (Jones et al., 2022). LCA can also be used to compare seaweed-based product with other products (see Section 2.3).

Innovation in production processes and transport can reduce the emissions, while innovation in productivity can increase yields and CO_2 uptake. Only if it is possible to produce substantially more energy from seaweed than what is needed for production it is a feasible option. In the same way, emissions for production and transportation must be considered for efforts to farm or collect seaweed for the purpose of sinking to calculate the net carbon balance.

6 | WHAT ARE THE POSSIBLE TRADE-OFFs?

A narrow focus on GHG emissions alone can lead to ignoring the adverse effects of each of the pathways. A general concern is that with increasing seaweed cultivation the production itself can reduce nutrient concentrations in the water below levels needed to maintain ecosystem quality (van der Meer, 2020). Alterations to the physical and biochemical environment can occur if the sector upscales production levels (Campbell et al., 2019) If the farm is too big and/or the cultivation too intense, nutrient uptake or shading can affect primary production (phytoplankton). By affecting the primary resources of the food chain, a tipping point can be reached, after which the ecosystem is affected beyond acceptable levels. In order to avoid nutrient depletion and keeping a marine system sustained with food production, the size of a farm should therefore be adapted to the carrying capacity of the ecosystem (van der Meer, 2020). In light of this, Froehlich et al. (2019) conclude that seaweed aquaculture might be able to offset carbon emissions of the global aquaculture sector but will not be able to offset the higher emissions of global agriculture.

Studies are starting to take these limits and negative impacts of upscaled cultivation into account (Jiang et al., 2022). Offshore aquaculture is being discussed for upscaled seaweed cultivation scenarios but to supply these farms with the necessary nutrients, artificial upwelling could be needed. Technology is not ready yet and would need to lower the costs to make the seaweed industry more profitable (Wu et al., 2020), while the question on the competition for nutrient remains also for offshore aquaculture. On the other hand, seaweed cultivation can also reduce impacts of eutrophication in sea areas with extensive nutrients loads from rivers (Racine et al., 2021). Further risks to be considered with seaweed aquaculture include, for example, the impact on the ecosystem through shading, effects of absorption of kinetic energy, spread of diseases or non-indigenous species, and so on. (Campbell et al., 2019), pollution, ecosystem change, effects on biodiversity, and impacts on birds and mammals (Spillias et al., 2022; van den Burg et al., 2020).

Based on a very simplistic calculation it will take about 8000 million tons of seaweed (12% C on Dry weight (DW) basis, DW = 10% of fresh weight; (Duarte et al., 2017) to sequester 1% of the 34.8 billion tons of CO_2 that was emitted in the global atmosphere in 2020 (Ritchie & Roser, 2020). With this, amount of seaweed about 1–5 million tons of phosphorous (0.1%–0.6% of DW; (Tibbetts et al., 2016) and 9–50 million tons of nitrogen (1.1%–6.3% of DW; (Tibbetts et al., 2016)) will also be extracted from the oceans. To put this into perspective, 8000 million tons is a large amount of biomass when compared to current global production of roughly 30 million tons.

Human induced sequestration—sinking seaweed to the ocean floor—comes with potential negative effects (Levin et al., 2023). It still needs to be investigated what exactly the ecological impacts are if pelagic *Sargassum* rafts, which are considered hot-spots of biodiversity, sink to the ocean floor (López-Contreras et al., 2021).

Gray et al. (2021) also calls to consider and study the potential impact on the deep-sea ecology that such a project like the artificially sinking of *Sargassum* could have, before implementing it on a wide scale. In the same line of argumentation, experts have come up with a list of impacts to be studied of effects on the deep-sea ecosystem when sinking biomass. For example, “changes in the abundance and species composition of benthic fauna related to the increase in organic carbon flux to the deep seabed”, “possible regional changes in community composition as operations scale up to the gigaton scale" or "effects on near-bottom hydro chemical conditions, particularly dissolved oxygen and pH changes associated with remineralization of sunken organic carbon"[12] all still need to be explored. Costa-Pierce and Chopin (2021) support this skepticism, reiterating that the impacts are simply unknown and further studies speak of probable biological threats, including changes to the microbial physiology and ecology and ocean chemistry (Boyd et al., 2022). As the (micro)biological activity is hampered by lack of oxygen, organic matter is preserved much longer in such dead zones than in a well oxygenated ecosystem (Jessen et al., 2017). From this perspective, dead zones would be the ideal locations for sequestration of carbon in organic matter. However, expanding dead zones to mitigate climate change would actively contribute to the further destruction of our benthic ecosystems. Actively sinking large amounts of seaweed to the deep sea might have similar impact on a depth that is not yet fully understood, and more research is needed (Ricart et al., 2022).

When considering seaweed for human consumption, research points to several concerns to be addressed. Iodine, (inorganic) arsenic, heavy metals, and pathogenic bacteria are among others relevant food safety hazards (Banach et al., 2020; Taylor & Jackson, 2016). Unknown consequences can be avoided by preventative measures for instance through good hygienic or manufacturing practices, food-safe procedures or protocols, or pre-site farm selection (Banach et al., 2022).

Regarding pathway 4 trade-offs, a study by Muizelaar et al. (2021) points toward potential negative impacts of adding seaweed to cows diet. Three effects were observed after feeding *Asparagopsis taxiformis* (1) reduced feed intake by lactating dairy cows, (2) the transfer of bromoform substances ($CHBr_3$) to urine and milk, and (3) abnormalities in the rumen wall. Concerns about the long term effects on productivity, animal health, product quality, digestibility of nutrients, compound residues in manure, and manure GHG emissions are also voiced (Vijn et al., 2020). Both short- and long-term animal trials are needed to comprehensively evaluate the use of seaweed in cattle production (Vijn et al., 2020). In vivo experiments are required to strengthen the evidence base for claims on methane reduction and better understand possible negative effects (Muizelaar et al., 2021).

7 | CONCLUSIONS

The aim of this article is to provide an overview of the different pathways that seaweed may contribute to climate mitigation and to make clear that there are drawbacks and trade-offs that need to be taken into account. Seaweed aquaculture and seaweed use can contribute to reduced emissions or sequestration of GHG. Confusion on the benefits of seaweed will eventually impede development of seaweed-based solutions. One risk is the incorrect mixing up of different pathways through which seaweed can be used. For this reason, the following four distinct pathways are identified:

1. Carbon sequestration where seaweed is grown and left in the seas.
2. Purposefully sinking seaweed to the deep-sea.
3. Emission reduction, where seaweed-based products replace products with a higher carbon footprint, either fossil-based products or other organic material.
4. Avoidance where seaweed products are used to avoid GHG emissions in other production processes.

Each of these pathways require methods to quantify impacts; in the sequestration pathways that requires monitoring of net carbon production and the amount of carbon that is eventually exported to the deep sea. Pathways 3 and 4 require LCA and/or Carbon Footprint with system boundaries set to include the production system itself and installation thereof.

With clarity on these pathways, policy measures can be developed that reward the sequestration of carbon by seaweed through carbon credits, stimulate seaweed-based products over alternatives with higher GHG emissions and reward the use of seaweed in other production chains. This all requires a clear discussion, and sufficient and solid evidence, on the role seaweed in climate mitigation. Research on quantifying carbon sequestration through natural processes from seaweed cultivation needs to continue, be consolidated and communicated, while the environmental impact on human induced carbon sinking needs thorough research. Concerns about animal health need to be addressed before one can safely reduce methane emission by feeding seaweed to cows. Claims on the climate and ecosystem benefits of seaweed cultivation and products compared to conventional products need to be validated. The contribution of this article is to clarify how climate change can be mitigated through seaweed, not all being through sequestration of carbon in the deep sea. Consuming and using seaweed products have a smaller carbon footprint, as well as adding carbon to certain production processes can reduce the amount of carbon in the air. These pathways can be used on different levels, by individuals in the supermarket, when investing in- or developing companies or on a governance level. It needs to be clear what is promised and what can be delivered to make seaweed an acknowledged climate mitigation solution.

AUTHOR CONTRIBUTIONS

Sander W. K. van den Burg: Conceptualization (equal); formal analysis (equal); funding acquisition (equal); methodology (equal); supervision (equal); writing – original draft (equal); writing – review and editing (equal). **Sophie J. I. Koch:** Conceptualization (equal); formal analysis (equal); investigation (equal); methodology (equal); writing – original draft (equal); writing – review and editing (equal). **Marnix Poelman:** Conceptualization (equal); funding acquisition (equal); investigation (equal); writing – review and editing (equal). **Jeroen Veraart:** Conceptualization (equal); investigation (equal); writing – original draft (equal). **Trond Selnes:** Investigation (equal); writing – original draft (equal); writing – review and editing (equal). **Edwin Foekema:** Formal analysis (equal); investigation (equal); writing – original draft (equal). **Romy Lansbergen:** Formal analysis (equal); investigation (equal); writing – original draft (equal); writing – review and editing (equal).

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CONFLICT OF INTEREST STATEMENT

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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ENDNOTES

[1] https://www.unglobalcompact.org/library/5974

[2] https://climatecleanup.org/

[3] https://www.aboutamazon.co.uk/news/sustainability/amazon-funds-the-worlds-first-commercial-scale-seaweed-farm-located-between-offshore-wind-turbines

[4] https://time.com/5848994/seaweed-climate-change-solution/

[5] https://www.newscientist.com/article/mg24632821-100-kelp-is-coming-how-seaweed-could-prevent-catastrophic-climate-change/#ixzz751Z1MRBA

[6] https://archive.ipcc.ch/ipccreports/sres/land_use/index.php?idp=74

[7] https://www.ipcc.ch/sr15/chapter/glossary/

[8] See, for example, https://www.oceans2050.com/

[9] https://www.runningtide.com/removing

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