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Can the Emerging European Seaweed Industry Contribute to Climate Change Mitigation by Enhancing Carbon Sequestration?

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ABSTRACT

Blue carbon habitats, which exhibit high rates of natural carbon sequestration, typically refer to salt marshes, seagrass meadows, and mangrove forests. Recent studies, however, have argued for the inclusion of seaweed-dominated habitats, like kelp forests, into blue carbon frameworks. Farmed seaweed may also function as a blue carbon habitat, with large-scale seaweed aquaculture suggested as a climate change mitigation strategy, but the evidence base remains limited. Here, existing knowledge on the mechanisms influencing carbon uptake, release, transport, and storage from kelp farms was synthesised, and a literature review was conducted to quantify associated rates of carbon sequestration. We identified strong geographical and methodological biases in the literature, with the majority of studies conducted in Asia and focusing on primary production rates as a proxy for carbon sequestration potential. Estimates of carbon release and storage rates were highly variable across locations, species, and approaches, and a scarcity of research on dissolved organic carbon, sedimentary carbon, and net ecosystem productivity was identified. Although the European kelp farming industry is in its infancy, it is predicted to expand to meet increasing demand for seaweed biomass. This is incentivised by perceived associated ecosystem service benefits such as enhanced carbon sequestration. However, multiple factors including environmental concerns, a lack of quantitative evidence, operational challenges, and regulatory complexities hinder industry expansion. Based on both the synthesised empirical evidence and an examination of key barriers and knowledge gaps, we identify future challenges and research priorities needed to assess the role of seaweed farming for climate change mitigation.

1 | Introduction

As a consequence of anthropogenic climate change, the average temperature of the Earth's surface is currently ~1.1°C warmer than in the late 19th century and warmer than at any time in (at least) the last 100,000 years [1]. While urgent and sharp reductions in greenhouse gas emissions are needed to curb the rate of warming, protecting and restoring habitats and ecosystems that naturally sequester carbon is an important component of climate change mitigation [2]. The term 'Blue Carbon' was introduced by Nellemann et al. [3] to highlight the significance of ocean ecosystems as global carbon sinks. Here, Nellemann et al. [3] defined Blue Carbon as the carbon captured by living marine organisms, in particular, vegetated ecosystems, such as seagrass meadows, mangrove forests, and saltmarshes, which are highly productive and can accrete carbon in their sediments [4]. These ecosystems comprise only 0.05% of terrestrial plant biomass and occupy just 0.5% of the global ocean floor, yet disproportionately contribute to natural carbon sequestration in the marine realm [3, 4].

Seaweed-dominated habitats have typically not been included in Blue Carbon frameworks because, unlike sedimentary Blue Carbon habitats that can store carbon locally, the carbon they produce is not accreted within the system but rather exported [5]. Nevertheless, the productivity of seaweed ecosystems is comparable to or even greater than saltmarshes and seagrass meadows, with a recent study reporting global average net primary productivity rates of 1711 g C $^{-2}$m–2 yr–1^{-1} for intertidal habitats and 656 g C $^{-2}$m–2 yr–1^{-1} for subtidal habitats [6]. Recent studies have called for the inclusion of seaweed habitats within Blue Carbon frameworks, given their high rates of productivity, extensive spatial extent (6.06–7.22 million km^2) and function as carbon donors within coastal ecosystems [6–9]. Moreover, first-order estimates suggest that ~11% of this primary production may be sequestered as either particulate organic carbon (POC) or dissolved organic carbon (DOC) in the deep sea or continental shelf sediments [10]. A recent national assessment of the carbon dioxide (CO_2) removal potential of shallow water ecosystems in Japan highlighted the importance of natural seaweed habitats, advocating for their inclusion in legal frameworks [11]. The high polyphenol content, carbon-to-nitrogen ratio, and productivity rates, combined with k-selected life history strategies of many seaweed species, increase the likelihood for seaweed-derived carbon to be sequestered into long-term sinks [12–17]. These characteristics make seaweeds, and especially kelp species, suitable Blue Carbon candidates. As such, enhanced carbon sequestration is being explored as a co-benefit of seaweed farming [18]. While the majority of cultivated biomass is harvested for food, cosmetic, pharmaceutical, biotechnological, fossil fuel-derived product replacements, and agri- or aquacultural industries [19–21], some biomass is released (as either detrital POC or solvated DOC) into the marine environment where it has the potential to reach storage habitats and be sequestered [18].

Globally, algal aquaculture production (for which values currently include microalgae and cyanobacteria) has increased by 244.5% between 2000 and 2022, with Asia accounting for the majority of growth [22]. The contributions of Asia, Africa, South America, North America, Oceania, and Europe to global production in 2022 were around 99.31%, 0.52%, 0.06%, 0.002%, 0.03%, and 0.08%, respectively [22]. The Asian seaweed farming industry is well-established, dating back to the 17th and 18th centuries in Japan [20]. Here, a wide range of species is cultivated, dominated by brown (~44.13%) and red (~55.77%) seaweeds [23]. Across Africa, the Americas, and Oceania, the majority of production in tonnes live weight (up to ~99.18%) in 2022 was attributed to red seaweed species, whereas production in Europe was dominated by brown seaweeds (98.11%), particularly kelp species [23]. This disparity is because warmer waters, associated with tropical latitudes, are unsuitable for kelp farming as they are primarily cold-adapted species [24]. In Europe, seaweed farming has intensified over recent years (Figure 1A), owing to increasing market demands for a range of applications and its reputation as a sustainable maritime industry that can support coastal economies. Moreover, seaweed farming aligns with several legal, policy, or educational instruments, including the United Nations Framework for Climate Change (UNFCCC) net-zero targets, the European Blue Growth Strategy (COM/2012/494 final), the EU Green Deal (COM/2019/640 final) and especially the Farm to Fork strategy (COM/2020/381 final), the UN Sustainable Development Goals (SDGs 5, 6, 13 and 14) and the UN Seaweed Manifesto, which further aligns with SDGs 2, 3, 8, 10, and 12 [26–37]. For example, in the United Kingdom (UK) alone, the first commercial seaweed farm was established in 2016 and, since then, approved license applications have increased almost 4-fold, mirroring the growth of the industry across wider Europe (Figure 1B). It should be noted, however, that approved licenses are not necessarily indicative of active biomass-producing seaweed farms but rather act as a gauge for interest and potential growth of the industry.

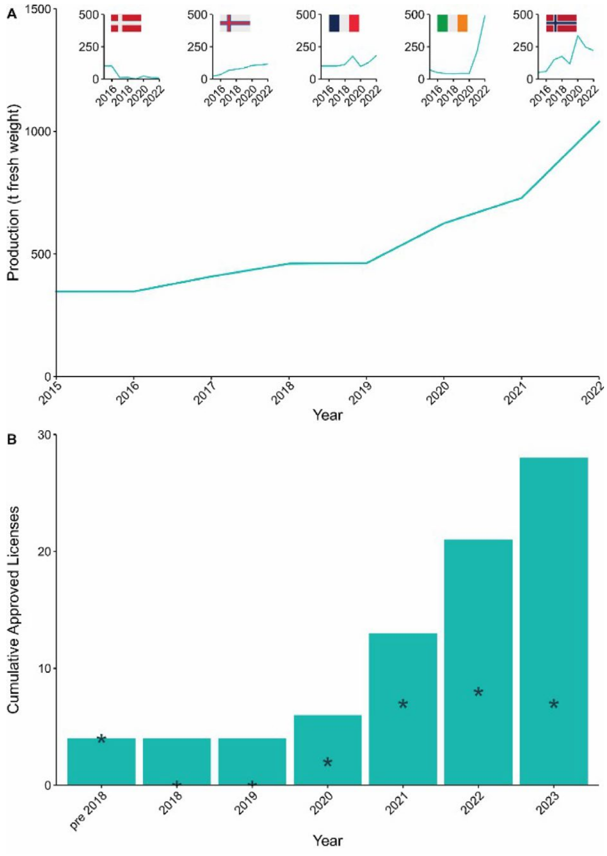

FIGURE 1 | (A) Seaweed aquaculture production (t fresh weight) in Europe over the last 7 years, with the production of (from left to right) Denmark, the Faroe Islands, France, Ireland, and Norway shown [25]. (B) The cumulative approved licenses for seaweed farms in the UK pooled from the Marine Management Organisation (England), National Resources Wales, Marine Directorate of the Scottish Government and Department of Agricultural, Environmental and Rural Affairs (Northern Ireland); asterisks indicate the number of approved licenses per year.

In Europe, seaweed biomass is primarily used for food (36%), food additives (15%), feed (10%) and cosmetics (17%) [38]. Fertilisers, biostimulants, pharmaceuticals, and other commercial applications of seaweed constitute comparatively minor applications [38]. In recent years, research efforts have been directed towards developing novel products as alternatives to high-carbon footprint foods, feeds, fuels and plastics, although the scale of product replacement remains low [28]. This research has been financially supported by the likes of the European Maritime and Fisheries Fund, the Horizon Europe funding programme and policy frameworks like the EU Marine Strategy Framework Directive (Directive 2008/56/EC) [39–41]. Irrespective of the ultimate use of the harvested biomass, an additional and passive benefit of seaweed farming could be the carbon captured within the biomass through photosynthesis, of which a proportion is subsequently released into the ocean [42]. For example, at a seaweed farm in China, Zhang et al. [43] found that up to 61% of gross primary production (GPP) was lost prior to harvest and released into the marine environment. Depending on the ultimate fate of this carbon, it has the potential to be sequestered (i.e., > 100 years) and subsequently contribute to climate change mitigation [10, 44].

A transition from wild harvesting to farming seaweed biomass is occurring across Europe [45], with a recent estimate of 97 companies wild harvesting, 75 producing biomass from aquaculture, and 19 performing both, to date [46]. This is in response to a growing demand for seaweed-derived products and the increased recognition of the impact of wild harvesting on some natural populations [47]. The knowledge base underpinning this emerging industry remains lacking in certain areas, particularly regarding interactions between aquaculture sites and the surrounding environment, and the wider benefits and ecosystem services provided by seaweed farming, particularly habitat provision and carbon sequestration [30, 48]. Despite these persisting knowledge gaps, nutrient extraction, bioenergy, novel products, and potential biodiversity and carbon credits in an emerging market incentivize the expansion of the seaweed industry in Europe [49].

In this review, we build on recent studies by Fujita et al. [50] and Pessarrodona et al. [51, 52] and focus on the European kelp farming industry to address the following questions: (1) what are the key processes influencing rates of carbon uptake, release, and sequestration by kelp farms?; (2) how much carbon is captured, exported, and sequestered through kelp farming? (3) what are the key knowledge gaps and barriers to kelp farming expansion in Europe?; and (4) can kelp farming make a significant contribution to climate change mitigation in Europe? We focus on kelp farming specifically, as these species are by far the most commonly cultivated in Europe, and we also draw on evidence from the farming of other seaweed species and in other regions more generally.

1.1 | What Are the Key Processes Influencing Rates of Carbon Uptake, Release and Sequestration From Kelp Farms?

Atmospheric CO_2, once dissolved in seawater (to form dissolved inorganic carbon, DIC), may be fixed within seaweed tissue via photosynthesis [53]. Carbon uptake rates vary across species, habitats, and environmental conditions. For example, the widely distributed northeast Atlantic species *Laminaria hyperborea* and *Laminaria ochroleuca* exhibit greater productivity, 0.78–0.87 g dry weight (DW) day^{-1} and 0.63 g DW day^{-1} respectively, than the co-occurring species *Laminaria digitata*, 0.39–0.49 g DW day^{-1}, and *Saccharina latissima*, 0.34 g DW day^{-1} [54, 55].

Furthermore, interacting abiotic factors play key roles in determining productivity rates. In commonly cultivated kelp species in Europe, *L. digitata*, *S. latissima*, and *Alaria esculenta* [56], growth is optimal between 10°C and 15°C, with > 16°C becoming stressful and ultimately lethal for the latter, and photosynthesis becomes saturated in all three species at levels of Photosynthetically Active Radiation (PAR) of ~30 $\mu mol\,m^{-2}\,s^{-1}$ [57–59]. Nutrient availability also mediates productivity in kelps, with growth rates falling when internal reserves of nitrogen deplete to < 1% of DW and/or environmental concentrations are < 1–2 μM [60–62]. Salinity is also important, as *A. esculenta* and *L. digitata* function optimally at salinities ranging from 30 to 40 psu, whereas *S. latissima* prefers lower salinities of 27–33 psu [63–65]. Additionally, water movement plays a critical role in the uptake of nutrients and carbon, and therefore productivity, with species-specific preferences. For example, *A. esculenta* prefers wave-exposed rocky shores whilst *S. latissima* is better adapted to wave-sheltered habitats [47, 64, 66]. In cultivated *S. latissima*, this pattern is reflected in increased growth with decreasing wave exposure [67].

For all farmed kelp species, the greatest rates of biomass accumulation coincide with optimal temperature and light levels/periods, and when nutrient concentrations are not limiting [47]. Across Europe, the widely cultivated *S. latissima* is generally deployed via seeded lines in winter, before peak growth is typically observed around the following March–May in Norway and Denmark [68–70], February–March in the UK and Ireland [71, 72] and November–February in Northern Spain [73]. During this cultivation period, some of the kelp biomass may be released into the ocean as either particulate organic carbon (POC; ≥ 0.2 μm) or dissolved organic carbon (DOC; < 0.2 μm) [42, 74]. Studies conducted in natural kelp forests have shown that up to ~95% of net primary productivity (NPP) may be released as POC, via the dislodgement of whole plants and chronic erosion of tissue, which is influenced by a range of biotic factors including grazing, disease, epiphytic loading, and seasonal life history patterns [75–77]. POC release rates are further mediated by abiotic factors including temperature, wave action, and nutrient availability [75, 76].

Once in the marine environment, POC will likely be degraded and consumed by microbes and detritivores, although it may remain photosynthetically active under suitable irradiance levels, potentially slowing decomposition rates and increasing the transport and storage potential [78]. The likelihood of kelp detritus in POC form being transported to, and stored within, carbon sink habitats (e.g., seagrass meadows, depositional sedimentary habitats, deep water masses or bottoms) is dependent upon several factors, including hydrodynamic processes (i.e., currents, wave action), distances between carbon source and sink habitats, seafloor topography, sedimentation rates, biochemical composition, and species and region-specific decomposition rates

[78–83]. For example, Wright et al. [81] found that while warm-temperate kelps in the northeast Atlantic exported more POC than their cold-temperate congeners, degradation of the former was 115% faster. Reduced degradation rates in cold-temperate kelp may be linked to having a higher carbon content than their warm-water counterparts, as well as a defense mechanism that reduces their palatability [81]. In a large-scale field experiment, Filbee-Dexter et al. [84] showed that ocean temperature was a key driver of decomposition rates of two kelp species, with slower breakdown associated with higher tissue-carbon content and colder conditions, which presumably led to slower microbial activity. This research suggests that continued ocean warming, leading to higher temperatures and shifts to warm-adapted species, may result in reduced carbon sequestration potential for natural kelp beds and also, in all likelihood, farmed kelp.

Few studies have directly measured DOC release by kelps in situ, and those conducted to date have reported high variability between individuals, species, and locations. For example, reports suggest that *Macrocystis pyrifera*, *Laminaria hyperborea*, and *Saccharina latissima* release $<10\%$, ~26%, and ~35% of fixed carbon, respectively, as DOC [85–87]. In *Macrocystis pyrifera*, individual DOC release ranged from ~2% to 24% of fixed carbon [88]. DOC is released passively (leakage) and actively (exudation) [89]. Leakage is associated with the diffusion of DOC across the cell membrane, which can be enhanced by cell damage caused by grazing, disease, or wave action, as well as cell death, changes in salinity, and desiccation [89]. Active exudation of DOC occurs because of cell maintenance, stoichiometric overflow, grazer deterrence, osmotic stress, and parental investment [89]. DOC, released from both detrital and living kelp biomass, is complex and comprised of different components that fall on a spectrum of bioavailability, from readily available, that is, labile (LDOC), to unavailable, that is, recalcitrant (RDOC) [89]. Furthermore, microbial activity in the form of bacterial degradation and viral lysis can transform LDOC into new molecular species of RDOC [90, 91]. Of the DOC released by kelp, ~40% is expected to remain recalcitrant, with this fraction more likely to be sequestered in long-term sinks [92].

Through ocean circulation, POC and DOC may enter the deep sea where they may be sequestered in long-term carbon sinks [93, 94]. Depending on particle sinking speeds and decomposition rates, hydrodynamic processes can transport kelp-derived POC over hundreds of kilometres and for hundreds of hours [79]. However, due to particle resuspension, sustained photosynthetic viability, and variable degradation rates, it is likely that the dispersal potential of POC may be underestimated [78, 80, 95, 96]. Once kelp-derived carbon sinks below the mixed layer or enters the deep sea, which occurs frequently [97, 98], it is likely to be removed from atmospheric exchange for timescales relevant to climate change mitigation, that is, >100 years [10], although this depends on the ventilation rates of the specific ocean system [99, 100]. Carbon deposited in shallower, coastal environments also has the potential to be sequestered [83, 101]. The accretion of seaweed-derived carbon in these areas is strongly linked to the extent of adjacent seaweed ecosystems, currents, and wave energy. Soft sediment is more conducive to carbon storage than rocky substrates, although rates of burial are highly variable and depend on many factors including sediment characteristics, deposition rates, bioturbation, and physical disturbance [10, 83, 102]. With a rising interest in carbon credits, and therefore interest in maximizing carbon finance opportunities, carbon sequestration associated with seaweed farming could be enhanced by placing farms in depositional environments [18].

Cultivation of kelp biomass will inevitably result in the release of POC and DOC into the immediate environment and therefore increase the local pool of carbon available for immediate cycling, re-release into the atmosphere, as well as sequestration. Delayed harvests, spatial planning, increasing farm yield by optimizing seeding and grow-out techniques, partial harvesting, artificial upwelling (pumping nutrient-rich water from depths to surface waters), and growing to sink biomass intentionally can increase the carbon sequestration potential of kelp farms by increasing the amount of carbon entering the marine environment [10, 32, 69, 103–105]. It should be noted, however, that artificial upwelling and growing seaweed biomass to sink remain controversial practices, as their impact on natural nutrient cycles is still unknown, and there are likely more valuable applications for the seaweed biomass [44, 106, 107].

1.2 | How Much Carbon Is Captured, Exported and Sequestered Through Kelp Farming?

To determine the carbon sequestration potential of kelp farming, a literature search was conducted (using Scopus and Google Scholar, searched up to September 2024) to identify peer-reviewed, original research articles (i.e., excluding literature reviews, pre-prints and opinion pieces) on the topic since the introduction of the "Blue Carbon" (BC) concept by Nellemann et al. [3]. The following search terms were queried:

ALL ("blue carbon" "kelp" "mariculture") AND DOCTYPE (ar) AND PUBYEAR > 2008 AND (LIMIT-TO (LANGUAGE, "English")).

ALL ("blue carbon" "kelp" "aquaculture") AND DOCTYPE (ar) AND PUBYEAR > 2008 AND (LIMIT-TO (LANGUAGE, "English")).

ALL ("carbon sequestration" "kelp" "aquaculture") AND DOCTYPE (ar) AND PUBYEAR > 2008 AND (LIMIT-TO (LANGUAGE, "English")).

ALL ("carbon sequestration" "kelp" "farming") AND DOCTYPE (ar) AND PUBYEAR > 2008 AND (LIMIT-TO (LANGUAGE, "English")).

ALL ("carbon sequestration" "kelp" "mariculture") AND DOCTYPE (ar) AND PUBYEAR > 2008 AND (LIMIT-TO (LANGUAGE, "English")).

Only publications available in English were considered, though it is noted that this will likely generate some geographical biases and could omit some of the significant research arising from Asia. Although given the volume of research returned from Asia (Figure 2B,C), we believe our results to be broadly representative. Titles and abstracts were initially screened for relevance, and articles that were not appropriate were removed, which resulted in a total of 50 papers. Details of the studies, such as location, target

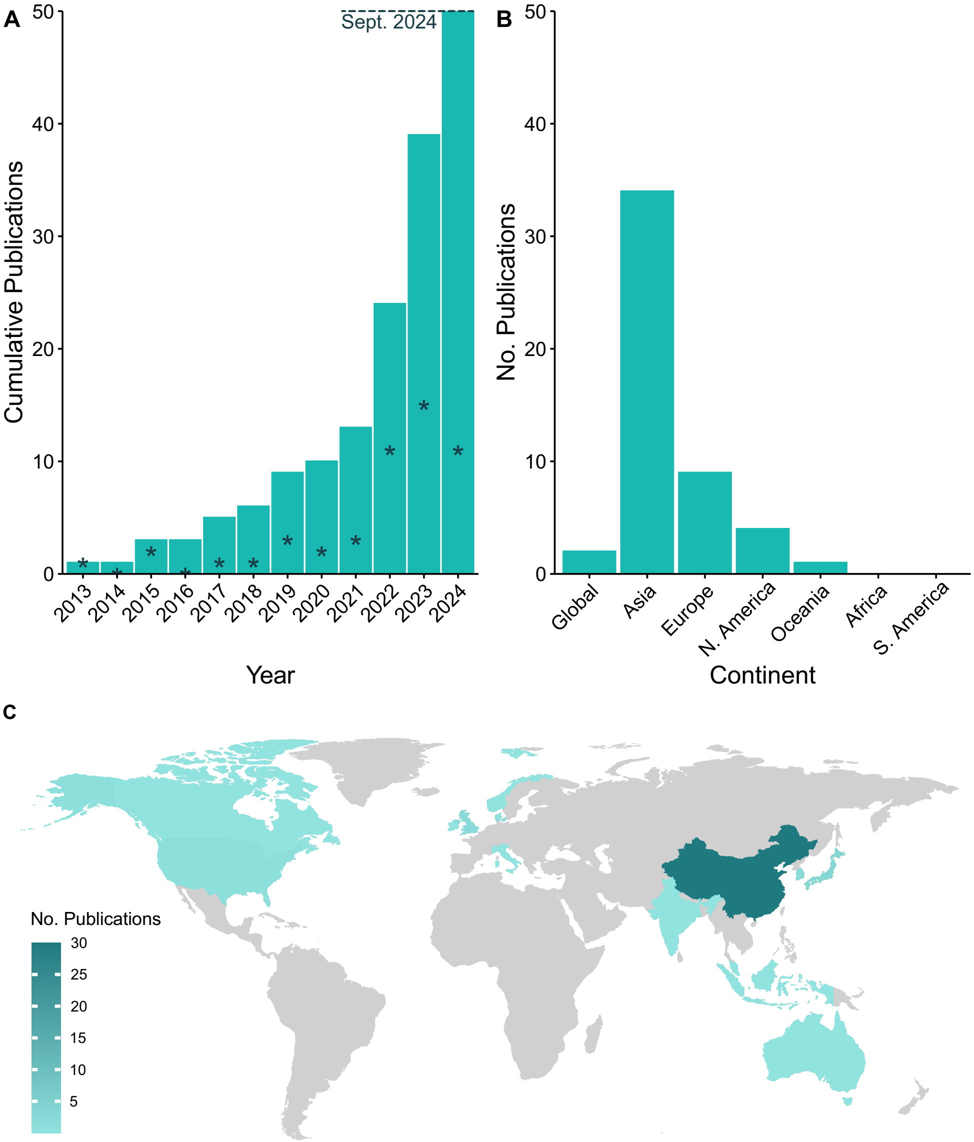

FIGURE 2 | The (A) cumulative number of relevant publications returned from the literature search (annual totals indicated with asterisks), (B) focal kelp species (shown by genus) of each study, with "Other" referring to genera that were less commonly targeted (specifically *Macrocystis* sp., *Alaria* sp. and *Nereocystis* sp.; five publications that targeted undefined "kelp" are not shown), (C) frequency of aquaculture systems explored across the studies, where "K" is kelp, "SW" is other seaweeds, "SF" is shellfish and "F" is fish, and (D) geographical origin/scope of the studies depicted on a global map. See Table S1 for full list of studies.

species, timeframe, methods, and key findings, were extracted and collated (Table S1). Papers were also classified by the broad methodological approach, in terms of whether they measured carbon removal (i.e., the amount of cultivated biomass removed from the system), dynamics of POC or DOC (i.e., the amount of organic carbon released into the environment), Net Ecosystem Productivity (NEP; i.e. the energy balance of the community) or sedimentary carbon (i.e., organic carbon content of sediments in and around farm sites), and whether studies focused on primary data collection or developing models informed by pre-existing data. Throughout the collation of this information, it was noted that the language used to describe carbon removal and carbon sequestration was often conflated, and *vice versa*, and that burial and storage were used interchangeably, meaning that it was difficult to determine which aspect and its corresponding values were being reported. For clarity, Blue Carbon terminology used within this review is defined and compared to that used in the literature search (Table 1).

The earliest relevant study returned in the search was conducted in Korea and was published in 2013 [108]. Between 2013 and 2021, few publications were returned (13 total), but since 2022, research efforts increased markedly (Figure 2A). Of these 50 publications, 4% were global estimates, 68% were conducted in Asia (predominantly China), 18% in Europe, 8% in North America, and 2% in Oceania, with no publications focusing on Africa or South America (Figure 2D). Primary data collection underpinned 58% of publications, and 42% presented results

TABLE 1 | Blue carbon terminology defined within this review and as used across the literature.

Blue carbon terminology	Defined in this review as
Capture Removal Assimilation	The drawdown and accumulation of atmospheric carbon within the biomass of the kelp.
Release	The proportion of (or rate of) kelp-derived carbon released into the marine environment as either POC or DOC.
Export	The proportion of (or rate of) kelp-derived carbon that is transported away from the source habitat, in this case the seaweed farm.
Burial	The proportion of (or rate of) kelp-derived carbon that reaches potential storage habitat and is buried following sedimentation.
Storage	The proportion of (or rate of) kelp-derived carbon that is stored within sediments over a period of time.
Sequestration	The proportion of (or rate of) kelp-derived carbon that is likely to remain stored/buried in sediments for geologically relevant timescales (> 100 years), in order to mitigate climate change. N.B. 'sequestration' is often used indiscriminately to describe carbon 'capture', and associated terminologies, 'burial' and 'storage' across the literature, and also often ignores the crucial aspect of timescale.

from models based on data from the literature. Kelp species belonging to the genus *Saccharina* were the primary focus of the majority of publications, followed by *Undaria* sp. and *Laminaria* sp. (Figure 2B). Less-studied genera included *Macrocystis* sp., *Alaria* spp., and *Nereocystis* sp., while five publications did not define which kelp species were explored (Figure 2B). With regards to the focal aquaculture system, kelp species were cultivated in isolation in 44% of publications, whereas 22% of studies focused on a combination of red, green, and brown algae, including kelp (Figure 2C). The remaining 34% of studies focused on integrated multitrophic aquaculture (IMTA) sites, of which seaweed-shellfish co-culture was the most common (Figure 2C). Carbon removal capacity, either modeled or directly measured based on productivity rates and carbon tissue content, was most commonly used to determine sequestration potential. Meanwhile, DOC release dynamics, sedimentary carbon stocks, and NEP were also examined within the context of carbon sequestration, but to a much lesser extent (Table S1).

Where possible, values were standardised to tonnes of carbon per hectare per year to allow for comparisons across regions and studies, although this was not always possible due to variations in methodologies or reporting across the literature (Table S1).

Carbon removal capacity varied across studies, from 0.05–3.5 t C ha^{-1} yr.$^{-1}$ in Europe [69, 109–112] and 0.19–9.83 t C ha^{-1} yr.$^{-1}$ in Asia [19, 108, 113–116]. The lowest carbon capture values are mostly derived from Life Cycle Assessments (LCAs) and field-based growth and loss measurements from single, small-scale *S. latissima* farms in Europe [67, 69, 110–112]. The greater, though more variable, carbon capture values returned from Asia could be attributed to the variety of methods applied (LCAs, TIC, DIC flux, NEP and modelled on national production) as well as the range of study species [19, 108, 113–116]. A field-based quantification of NEP showed that farmed *U. pinnatifida* in Japan captured 0.09–0.40 t C ha^{-1} yr.$^{-1}$, within the range of European LCAs and field-based measurements of *S. latissima*, DIC flux measurements of *S. japonica* culture in China [19, 67, 69, 110–113]. Furthermore, Berger et al. [117] estimated that from 2006 to 2010, 0.21–0.39 Gt C yr.$^{-1}$ was captured by idealised seaweed farming in Exclusive Economic Zones, determined from a high-resolution ocean biogeochemical model, global production values and carbon content and growth rates of *S. latissima*, *L. digitata* and *M. pyrifera*. Meanwhile, Wu et al. [118] forecasted that in the next 80 years, under the IPCC's intermediate mitigation scenario Representative Concentration Pathway (RCP) 4.5, which aims to limit global warming to below 2°C, this global carbon removal rate could be increased by up to 16 times (~26 times with artificial upwelling) through open-ocean aquaculture and sinking [119]. Artificial upwelling, the process of pumping nutrient-rich water to the surface to enhance primary production, and deliberately sinking seaweed biomass to remove carbon from the atmosphere, are controversial practices. This is because the impacts of displacing or enhancing nutrient inputs from the deep sea are largely unknown [106, 120]. Clearly, methods designed to enhance the climate change mitigation potential of seaweed farming should be treated cautiously until a robust evidence base has been developed.

Kelp farming in Europe returned the lowest carbon sequestration potentials, ranging from ~0.01 to 0.02 t C ha^{-1} yr.$^{-1}$, determined using field-based measurements from single, small-scale *S. latissima* farms [71]. However, under a site suitability model that identified >1 million km^2 of potential cultivation area in EU Atlantic regions and considered the production of *Alaria* sp., *Laminaria* sp., *S. latissima*, and *U. pinnatifida*, a carbon sequestration capacity of <6.09 t C ha^{-1} yr.$^{-1}$ was projected [121]. In North America, modelled carbon sequestration potentials of *S. latissima*, *A. marginata*, and *N. luetkeana* returned more conservative estimates (0.02–0.42 t C ha^{-1} yr.$^{-1}$) [122, 123] than field-based measurements (1.1–1.8 t C ha^{-1} yr.$^{-1}$) [124]. Across Asia, model-derived potentials ranged from 0.76–5.21 t ha^{-1} yr.$^{-1}$ [114, 125, 126]. A similarly high potential of 5.45 t C ha^{-1} yr.$^{-1}$, also determined through modelling, was predicted for Oceania [127]. While differences in cultivated species and environmental conditions may explain some variation, the methodologies applied are notably different. Generally, the greatest carbon sequestration values were obtained from models using either national annual production of *Laminaria* sp., *U. pinnatifida*, and *S. japonica* in China [114, 125], LCAs on *S. japonica* also in China [126] and different socio-economic, operational, and growth scenarios applied to *M. pyrifera* in Australia [127].

DOC release dynamics were only explored in research returned from Asia, with the majority of contributions from China and focusing on *S. japonica* [91, 92, 126, 128–134]. Generally, values were reported variably and therefore comparisons were difficult to draw. Where comparisons could be made, the release of DOC ranged from 0.08 to 7.0 mg C (g DW)$^{-1}$ d^{-1} (incubated *S. japonica*) [92, 135] to 6.2 mg C (g DW)$^{-1}$ d^{-1} (environmental sampling from kelp culture) [91]. However, modeled DOC release, enhanced by artificial upwelling, by *Laminaria* sp. and *Undaria* sp. was orders of magnitude greater (~0.18 kt C yr.$^{-1}$) [134]. The fraction of DOC that remained as RDOC, and therefore likely for sequestration, ranged from 5% to 58% [92, 128–131, 133]. More generally, environmental DOC concentrations were greater in kelp cultivation zones than in shellfish or control zones, suggesting that kelp plays an important role in local carbon cycles [130].

Further variability was identified among sedimentary organic carbon stocks associated with kelp farming. In seaweed culture (including kelp), sedimentary TOC ranged from 0.53% to 0.68%, comparable to TOC in control sites [136]. In kelp-shellfish co-culture, sedimentary TOC ranged from 0.89% to 1.21% and was greater compared to control sites [137, 138]. However, in contrast, TOC was also comparable between kelp, shellfish, and fish culture in another study [139].

Although variation between studies and regions could be attributed, at least in part, to the different target species, the lack of primary data collected from seaweed farms likely remains an issue. While the limited body of literature collated in the present study is mostly cautiously optimistic about the carbon sequestration potential of kelp farming, there remain significant uncertainties relating to the efficacy of kelp farming as a Blue Carbon strategy. This likely stems from persisting knowledge gaps, ranging from determining the ultimate fate of kelp farm-derived carbon to developing legislative and industry frameworks.

1.3 | What Are the Key Knowledge Gaps and Barriers to Kelp Farming Expansion in Europe?

The Atlantic coastline of northwest Europe is vast and complex, with cool, nutrient-rich waters conducive to kelp farming. In contrast, the warmer waters of the Mediterranean Sea are close to or in excess of the upper thermal limits of many kelp species and, as an oligotrophic system, it lacks the necessary nutrients for kelp farming, although other seaweed species can be grown. In both the Baltic and Black Sea, high nutrients as well as low salinity and light can become limiting, and as such, large areas are unsuitable for seaweed cultivation [121]. There remain in these systems, however, multiple barriers to upscaling kelp cultivation and growing the seaweed industry, as highlighted in the Blue Economy Roadmap [140]. The most significant barriers relate to the following overarching themes: (i) licensing, regulation and marine spatial planning; (ii) operations, logistics and supply chains, processing and demand; (iii) knowledge gaps pertaining to the environmental impacts and benefits of farming.

In relation to the first barrier, the current systems in place for planning and licensing impede industry expansion. Aquaculture in Europe is managed under a polycentric governance system, meaning that compliance with regulations outlined by different institutions within the governance hierarchy must be obtained [141]. For example, in the UK, Ireland and Norway this is further complicated by the involvement of multiple government agencies and departments from which consent must be obtained, and a lack of publicly available data to support license applications [27, 141–143]. The inflexible nature of the current systems does not reflect the inherently dynamic nature of the marine environment nor does it support the sector's capacity to become more sustainable and resilient [141]. Moving forward, particularly as sustainability and future-proofing sectors such as the aquaculture industry becomes imperative to preparing for future global challenges, regulatory systems should evolve [144–147]. Under the "Multiannual National Strategic Plans (MNSPs) for development of Aquaculture for the period 2021–2030" (COM/2021/236 final) EU member states outline country-specific targets for encouraging sector growth, supported by the European Maritime and Fisheries Fund (EMFF) other EU funds [148]. The Plan calls for the streamlining of existing legislation, creating single national aquaculture entities that encompass all relevant aquaculture authorities, moving to a "one-stop-shop" system for licensing and enhancing process transparency, designating suitable aquaculture sites and supporting long-term licensing through improved monitoring and licence revocation [148]. Subsequent actions include the launch of the web-based "Aquaculture Application and Monitoring System" (AQUAMIS) by The Department of Agriculture, Food and Marine in Ireland [149] and the EU TAPAS project which aims to develop accessible management tools and practices [150].

A further consideration for the successful expansion of the European industry is the implementation of social licensing, which is a framework that supports a mutually beneficial relationship between a business and its host community [151]. To minimize conflict between stakeholders and local communities, social licensing provides economic and socio-political legitimacy as well as interpersonal and inter-organizational trust [152]. In the context of seaweed farming, these aspects will be crucial in influencing social acceptance of the growing sector as well as its operational viability, associated legislation, and commodity value [151]. Social licensing has proven successful across various sectors, such as energy (onshore windfarms) in Scotland and forestry in Sweden [153, 154]. In Europe, social licensing of seaweed farming has been explored conceptually in Scotland, Northern Ireland, Ireland, and France but is yet to be formally adopted [155, 156].

With regard to the second barrier, although some kelp farming practices are relatively well established in Europe, the wider seaweed industry faces multiple challenges [143]. These include issues with technological and operational optimisation, poorly developed supply chains, market uncertainty, and achieving economically viable scales [49, 56, 143, 157, 158]. This calls for investment into the infrastructure required to develop processing, logistics, and product chains, as well as financial support to assist new, small businesses [143, 157]. The use of pre-existing farm infrastructure (e.g., header lines, anchors) and distribution networks (e.g., processing, transport), established by other low-trophic aquaculture facilities (e.g., mussels, oysters), could cost-effectively support the upscaling of seaweed cultivation [159]. Bringing seaweed products to market is another issue, whether for human consumption, animal feed, fertilisers, bio-compounds, or carbon credits. For example, although seaweeds were historically consumed in Europe, the current social perception of the direct consumption of seaweed is sceptical [157]. To date, the majority of seaweed produced in Europe is for phycocolloid production required in food and food-related industries as thickening agents in processed commodities, like dairy products and toothpaste [160, 161]. Here, the raw seaweed ingredient is not declared; rather, the extracted compounds are listed, and as such, the general public is unaware of their day-to-day seaweed consumption. Therefore, it is important to incentivise product desirability and shift social perceptions to integrate these products [157]. A significant step towards this was the addition of further algae species to the EU Novel Food Status Catalogue, which identifies which foods and ingredients can be sold in the EU and which require Novel Food Regulation authorisation [144, 145]. This is particularly relevant to future food security and climate change mitigation, as seaweed offers a low-carbon alternative that avoids future challenges faced by the agriculture industry [146].

Finally, small-scale low-trophic farming likely poses low environmental risks [147]. Nevertheless, there are valid concerns regarding the environmental impacts of upscaling kelp farming, including the effects on local hydrodynamics, water quality, biosecurity (invasive species, pathogens and genetic risk), marine flora and fauna, and the production of ozone-depleting volatile halocarbons by seaweeds [142, 143, 147, 158]. The level of risk associated with these is poorly described by the primary literature, which has resulted in a conservative risk ranking to anticipate negative impacts [147]. Moreover, most of the research published on biodiversity monitoring or interactions with surrounding water bodies has been conducted at small-scale commercial or pilot cultivation sites [48, 162, 163], which makes scaling up any observed impacts or benefits challenging. Modelling approaches that aim to predict the impacts of scaling up in terms of ecological carrying capacity and competition for resources with phytoplankton [164], for example, can help to fill this gap. Current and future research priorities relate to monitoring genetic diversity and pathogen prevalence, nutrient extraction, and dissolved organic material release as well as modelling, supported by in situ measurements, changes to the physical environment (current flow, sedimentation, light penetration etc.) [56, 142, 147]. Subsequent findings will facilitate informed decision-making on scale-dependent risk mitigation and management strategies [147].

For the European seaweed industry to deliver meaningful ecosystem services, like carbon capture, the sector must scale up. To achieve this, a concerted approach to overcoming the three broad barriers outlined above will be necessary. Projects like multi-national "Community driven farming for the Atlantic and Arctic Sea basins through Regenerative aquaculture" (C-FAARER), funded by Horizon Europe, and the "Irish Macro-Algal Cultivation Strategy to 2030", proposed by Ireland's Seafood Development Agency (BIM,) aim to address these issues by providing a roadmap and guidance for expansion, and identifying opportunities for expansion [165, 166].

1.4 | Can Kelp Farming Make a Significant Contribution to Climate Change Mitigation in Europe?

The European seaweed farming industry is in its infancy but gaining traction, in part incentivised by its potential to mitigate climate change through enhanced carbon sequestration. Though underpinned by a limited evidence base, the scientific community appears optimistic about this potential, provided that the most pressing knowledge gaps are urgently addressed. This includes quantifying the proportion of carbon (as POC, PIC, DOC, DIC) generated by a seaweed farm that does not enter the short-term carbon cycle but rather is sequestered in the long term, in any compartment (sediments, seawater, tissue etc.) [52]. Furthermore, to effectively mitigate climate change through carbon sequestration, it is crucial to ensure that CO_2 fixed by seaweeds is removed from the atmosphere. Due to the temporal decoupling of photosynthesis and the air-sea CO_2 re-equilibrium, this cannot be assumed in all cases [167]. Additionally, the release of volatile organic compounds (VOCs) from seaweeds, such as dimethyl sulfide (DMS) and bromoform, can influence climate through various processes, including enhancing local cloud formation and interacting with the ozone layer [168]. Yet, these processes have been largely overlooked, globally and regionally, yet fundamentally require addressing to accurately assess the overall contribution of seaweed farming to climate change mitigation [167–169].

Quantifying different carbon pathways is essential for determining the basic criteria for developing carbon markets, that is, additionality, permanence, and leakage. Additionality describes the carbon removal capacity introduced by carbon capture or mitigating activities, in addition to the natural system [170]. Permanence refers to the long-term removal of CO_2, which has been defined as >100 years [44, 170]. Meanwhile, leakage is the redirection of emissions elsewhere as a result of mitigating activities [170]. This means that kelp farming can only be incorporated into carbon credit schemes if the carbon removal capacity of the existing system is significantly increased, the carbon removed remains sequestered for >100 years, and emissions are not increased elsewhere as a result, particularly through hatchery, operational, and post-harvest activities [170]. Aspects of these criteria can be described through LCAs, which are crucial, in part, for determining how the seaweed industry contributes to climate change aside from carbon removal within the marine environment during the cultivation stage, like during hatchery and processing stages [33, 171, 172]. That said, there is clear potential for the continued expansion of the seaweed sector in Europe, with valorisation strategies focused on biorefining seaweed biomass for high-value products in the pharmaceutical, cosmetic, and food industries [173]. Rather than a primary focus on direct carbon sequestration, seaweed farming may contribute to the wider bioeconomy and circular economies, with significant environmental, economic, and societal benefits [173, 174].

With currently a negligible contribution to global production, it is assumed that the emerging European seaweed farming industry minimally aids emissions removal [25]. While scaling up, the industry is primarily driven by growing market demands and future food security, the added benefit of climate change mitigation through carbon sequestration is likely to also increase. However, the ecological impacts are largely unknown; the market is underdeveloped, and the present regulatory frameworks are a bottleneck to industry growth. It is critical to quantify the current carbon sequestration potential of kelp farming on a regional scale to inform upscaled climate change mitigation capacity and impacts, but also to establish a geographically unbiased global picture. This developing field offers the scope for interdisciplinary collaboration between researchers, industry, and regulators to not only quantify carbon dynamics but also create a sustainable industry supported by legislative frameworks. This, in turn, can be integrated with other developments such as offshore wind farm expansion and strategies including The Global Ocean Alliance's (GAO) '30 by 30', which aims to protect at least 30% of the global ocean by the end of the decade [175].

In addition to potential climate change mitigating benefits of kelp farming, local ocean acidification and deoxygenation alleviation may also occur [30]. Seaweed farming has been shown to raise the pH and dissolved oxygen concentrations of surrounding seawater, thereby buffering ocean acidification and deoxygenation at local scales [176, 177]. Consequently, a further co-benefit of seaweed farming may be the creation of potential refugia for marine organisms, such as co-cultivated shellfish, from these climate change-related stressors. Nevertheless, the knowledge base underpinning this remains equally uncertain, with highly variable data and unknown impacts of scaling-up [178].

In this review, we have focussed on the climate change mitigation potential of seaweed farming that relates to the release and storage of additional carbon in the marine environment. However, there is also potential for algal aquaculture to contribute to climate change mitigation if seaweed products (or by-products) can replace high-carbon footprint commodities, which may be fossil-fuel based (e.g., plastic) and/or depend on fossil-fuel input (e.g., mineral fertilizers). Research in this area has explored the potential for seaweed-derived product replacements, although the scale and pace of this transition remain limited to date [171, 179, 180].

Regardless of the future potential of seaweed farming to mitigate climate change through carbon sequestration or to alleviate local ocean acidification and deoxygenation, the importance of maintaining and restoring natural Blue Carbon ecosystems should not be downplayed. Globally, the cultivated area is estimated to be 0.06% of the extent covered by natural seaweed habitats [52]. Furthermore, Duarte et al. [7] showed that the global NPP of seaweed farming (0.002 Gt C $yr.^{-1}$) is lower than that of subtidal brown seaweed habitats (0.917 Gt C $yr.^{-1}$), which are dominated by highly productive and extensive kelp and fucoid forests. Of this global brown seaweed production, 15% is expected to be exported, with up to 0.044 Gt C $yr.^{-1}$ predicted to be sequestered in the deep sea for 100 years or more [10, 94].

2 | Conclusion

In conclusion, the present literature review has highlighted the need for targeted research that quantifies carbon dynamics, including release, transport, and burial, in and around a wide range of seaweed farm scenarios under different environmental, operational, and socioeconomic contexts. Whilst some of these aspects have been explored in natural kelp beds, there is a distinct lack of research that focuses on farmed kelp, particularly in Europe [69, 79, 82]. Additionally, the language used around carbon sequestration is a source of confusion. Therefore, we propose using standardised terminology with suitable definitions, such as those presented in Table 1, to support comparable research outputs and communication across the academic, industry, and government sectors. From the literature review, we provide some evidence to support the role of seaweed farming in terms of enhancing local carbon sequestration, but to evaluate and quantify it correctly, addressing persisting knowledge gaps within the field is essential. More generally, whether the European seaweed industry can be scaled up quickly enough to make a meaningful contribution to climate change mitigation remains unclear and perhaps unlikely.

Author Contributions

Maxine C. Canvin: conceptualization, writing – original draft, methodology, writing – review and editing. **Ana R. Borrero-Santiago:** writing – review and editing, resources. **Tom Brook:** writing – review and editing, resources. **Mollie Gupta:** writing – review and editing, resources. **Jessica Knoop:** writing – review and editing, resources. **Georgina Menage:** resources. **Pippa J. Moore:** conceptualization, writing – review and editing, funding acquisition, supervision. **Nessa E. O'Connor:** writing – review and editing, resources. **Aurora M. Ricart:** writing – review and editing, resources. **Dan A. Smale:** conceptualization, writing – review and editing, funding acquisition, supervision.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.