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Assessing the Feasibility of Seaweed Farm-Offshore Wind Co-Location in New Jersey

Brianna Delaney Reynolds

ABSTRACT

New Jersey's offshore wind energy sector may provide an opportunity to advance the seaweed farming industry through ocean multi-use. Yet, opportunities, constraints, and knowledge gaps for seaweed farm-offshore wind co-location remain largely uninvestigated. Here, I determine the suitability of native seaweed species for offshore cultivation in New Jersey and conduct a quick scoping review (QSR) to assess the knowledge base surrounding seaweed farm-offshore wind multi-use. *Saccharina latissima* and *Fucus vesiculosus* were identified as native species with commercial value for cultivation in New Jersey. Yet, offshore waters at the location of a wind development site had insufficient nutrients to meet the growth requirements of these species. The QSR indicated a stronger emphasis on provisioning ecosystem services (i.e., food and agriculture products) than regulating/habitat and cultural services, when seaweed farms are co-located with offshore wind, as compared to seaweed farming in general. Stronger emphasis was also placed on environmental constraints when seaweed farms are co-located with offshore wind, including competition with local communities, risks to marine mammals/birds, and reduced primary production. Finally, there was a stronger emphasis on legal knowledge gaps for seaweed farming when co-located with offshore wind, particularly with respect to the governance of multi-use sites. To overcome these constraints and knowledge gaps for seaweed farm-offshore wind multi-use, future research should focus on nutrient limitation to farms, marine ecosystem effects, and the legal governance of multi-use sites with marine spatial planning.

Keywords: seaweed, macroalgae, cultivation, offshore wind, multi-use

MONTCLAIR STATE UNIVERSITY

Assessing the Feasibility of Seaweed Farm-Offshore Wind Co-Location in New Jersey

by

Brianna Delaney Reynolds

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CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

As the demand for sustainable marine food and resources increases, enhancement of the blue economy could meet this demand through the aquaculture sector (Costello et al., 2020). In 2020, the global aquaculture industry produced 122.6 million tons (live weight) of aquaculture products, of which 87.5 and 35.1 million tons of aquatic animals and algae were produced, respectively (FAO, 2022). The total aquaculture production of 2020 was estimated at 281.5 billion USD, and Asian countries contributed the most to this value (75.0%), followed by countries in the Americas (10.0%) and Europe (8.0%) (FAO, 2022). Seaweed farming, or the cultivation of marine macroalgae species, is a sector of the aquaculture industry that does not require the use of arable land, freshwater, or the input of fertilizers or feed, and thus has the potential to alleviate pressures on land-based resources to address global food security (Cai et al., 2021; UNEP, 2023).

Worldwide, the seaweed farming industry is continuing to grow as the demand for seaweed products increases (Chopin and Tacon, 2021). The global cultivation of seaweeds nearly tripled from 12 million tons in the year 2000 to 35.10 million tons in 2020 and increased by half a million tons between 2019 and 2020 alone (FAO, 2022). The global leaders in seaweed production for the year 2020 were China (58.0% of production), Indonesia (27.0% of production), and the Republic of Korea (5.0% of production) (FAO, 2022). Across the world, 31 species of seaweed are recognized in the aquaculture industry and are exported for use in a variety of products (FAO, 2022).

Human consumption of seaweeds has a rich history dating back centuries and is particularly prominent in Eastern Asian cuisine such as soups, salads, and sushi wraps (Cai et al., 2021). Seaweeds can be highly nutritious, rich in dietary fibers and protein, and some studies have shown their potential to improve health and reduce risks of illnesses (Cai et al., 2021). However, seaweeds grown in contaminated waters may accumulate heavy metals, such as cadmium and inorganic arsenic, which can cause adverse health effects when consumed (FAO and WHO, 2022). Therefore, seaweeds grown for human consumption require careful monitoring and management to reduce health risks (FAO and WHO, 2022). Seaweed products also have a wide range of uses in the form of raw materials, primarily hydrocolloids such as agar, carrageenan, and alginate. Hydrocolloids are used as food additives for emulsification but are also prominent in cosmetic, pharmaceutical, and medicinal products (Cai et al., 2021).

Additionally, seaweed farms serve economic and environmental roles (Cai et al., 2021). For example, coastal communities can find employment across the value chain (i.e., nursery, harvest, post-harvest) and with it a source of income (Valderrama, 2012). This diversification of livelihoods contributes to women's empowerment and may reduce pressure on local fisheries (Larson et al., 2021; Sievanan et al., 2005). However, socioeconomic risks related to seaweed farming also have been identified in the form of adverse health effects of the seaweed farming livelihood (i.e., fatigue, respiratory problems, injuries from hazards in the water like shells or sea urchins), and low income due to volatile market prices and farmers who lack information and material resources (UNEP, 2023).

Seaweed farming may also play a role in climate change mitigation and adaptation by buffering ocean acidification, oxygenating hypoxic waters, improving water quality via bioremediation and nutrient absorption, and protecting coastlines from strong wave action; however, these benefits can be context and locale specific (UNEP, 2023). Emerging research also indicates the potential for seaweed farms to capture and sequester atmospheric carbon dioxide, yet the magnitude of this sequestration is still under investigation (UNEP, 2023). One analysis of carbon sequestration from seaweed farming suggests the need to drastically increase the scale of production to reach a globally relevant carbon sink (emLAB, 2019). Moreover, the potential for carbon reduction through the replacement of carbon-intensive products with low-carbon seaweed-based products has received increasing attention (UNEP, 2023). Environmental risks such as competition with wild habitats for resources, introduction of pathogens or non-native species, genetic pollution, and entanglement of marine megafauna may also be associated with seaweed farming and require consideration, particularly at increased production scales (UNEP, 2023).

The USA is 17th in global aquaculture production, valuing roughly $1.5 billion USD across all aquaculture sectors (i.e., shellfish, finfish, algae) (NJDA, 2021). Yet, despite growing interest across the globe, seaweed farming remains a nascent activity in the USA (Kim et al., 2019). In 2020, the USA produced only 0.30 tons of cultivated seaweeds, accounting for a mere 0.083% of total global seaweed production (FAO, 2022). Seaweeds, primarily kelps, are currently cultivated in California, New York, Washington, Alaska, and throughout New England at various scales of production (Kim et al., 2019). In New Jersey, aquaculture production is primarily focused on mollusks, such as clams and oysters; however, the New Jersey Department of Agriculture (NJDA) has issued a call to action for the implementation of a regional seaweed farming industry to diversify aquaculture livelihoods (NJDA, 2021). In their 2021 Aquaculture Development Plan, the NJDA states a need to “develop a mechanism to enable pilot programs that advance aquaculture of native macroalgal candidate species in State waters” (NJDA, 2021). Key barriers to the implementation of seaweed farming in New Jersey are the identification of native species with traits appropriate for cultivation, and selection of appropriate marine space for farming that does not conflict with other ocean uses.

In September of 2022, New Jersey's Governor, Phil Murphy, signed executive order 307, setting a goal of 50% clean energy by the year 2030 and 100% clean energy by 2050 (Exec. Order No. 307, 2022). To fulfill this goal, offshore wind energy is projected to produce 11,000 megawatts of energy by 2040 (Exec. Order No. 307, 2022). The development of New Jersey's offshore wind sector may provide an opportunity to develop a statewide seaweed farming industry through ocean multi-use. Implementing seaweed farming within the blueprint of offshore wind farms could optimize the use of ocean space, reduce production costs through shared infrastructure and other resources, and support local marine biodiversity (Buck et al., 2008). However, research regarding the feasibility of co-locating seaweed farms with offshore wind, including environmental and socioeconomic opportunities, constraints, and knowledge gaps, remains scarce.

In the present study, the current state of knowledge regarding the co-location of seaweed farming and offshore wind is investigated and applied to the existing framework of New Jersey's aquaculture and offshore wind industry. The following research questions are addressed: 1) Are there native seaweed species with commercial value in New Jersey that could theoretically be cultivated within an offshore wind farm? 2) Based on global literature, what are the potential constraints, opportunities, and knowledge gaps for co-location of seaweed farms with offshore wind energy? To address these questions, the environmental growth requirements of native seaweed species (i.e., temperature, salinity, and dissolved inorganic nutrients) were compared from published literature to the environmental oceanographic data from NOAA's World Ocean Atlas (WOA18) near a proposed wind development site in New Jersey (Ocean Wind 1). Further, a quick scoping review (QSR) was conducted to quantitatively assess evidence in the scientific literature for constraints, opportunities, and knowledge gaps in the co-location of seaweed farming with offshore wind.

METHODS

Identification of Potential Species for Cultivation

To determine whether there are native seaweed species with commercial value suitable for offshore cultivation in New Jersey, we first downloaded environmental oceanographic data files from the WOA18 Data Access (Boyer et al., 2018) at coordinates nearest the proposed Ocean Wind 1 site (39.197°N, 74.236°W; US Gov, 2019): temperature (°C) and salinity (psu): 39.125°N, 75.375°W; phosphate (µmol/kg) and nitrate (µmol/kg): 39.500°N, 73.500°W. Oceanographic data were averaged seasonally (spring: Apr-Jun, summer: Jul-Sep, fall: Oct-Dec, winter: Jan-Mar) and across 0–35 m depth from 1955–2017 to provide a broad baseline of oceanographic conditions. Temperature, salinity, phosphate, and nitrate were the focal datasets, as these oceanographic factors commonly limit seaweed growth (Bruhn et al., 2016; Roleda and Hurd, 2019).

For comparison with the oceanographic data, environmental growth requirements were mined from the literature for *S. latissima* and *F. vesiculosus*, two species identified via literature searches as having potential for cultivation: they are known habitat formers, are native to Northwestern Atlantic waters and found in New Jersey (Egan and Yarish, 1988; Muhlin and Brawley, 2009), and have an established commercial value in the global aquaculture industry (Peteiro and Freire, 2009; Rupérez et al., 2002). Nine and five studies were identified summarizing the environmental growth requirements of *S. latissima* and *F. vesiculosus*, respectively. From all literature sources, ranges of requirements (minimum to maximum) for temperature, salinity, and dissolved inorganic nutrients were determined for each species. Data came from populations across New York, New Jersey, the Atlantic Coast of Nova Scotia, Southern New England, the Atlantic Coast of Europe, the Baltic and Irish Seas, Denmark, and Norway.

This analysis was not intended as an exhaustive assessment of all seaweed species suitable for cultivation in New Jersey, rather it provided a first step towards assessing the potential for seaweed cultivation of two species at a proposed offshore wind farm.

Quick Scoping Review

To quantify the current state of knowledge in seaweed farming multi-use identified by scientists, a quick scoping review (QSR) was conducted. The QSR was a systematic search that identified existing scientific literature on seaweed farm-offshore wind multi-use and aimed to collate existing evidence to provide a global perspective and inform policy and future research. The QSR identified peer-reviewed, English language, scientific journal articles that address seaweed farming and its associated ecosystem services, with a special focus on the use of seaweed farming in a multi-use project. The QSR was conducted in three distinct screening steps (**Figure 1**).

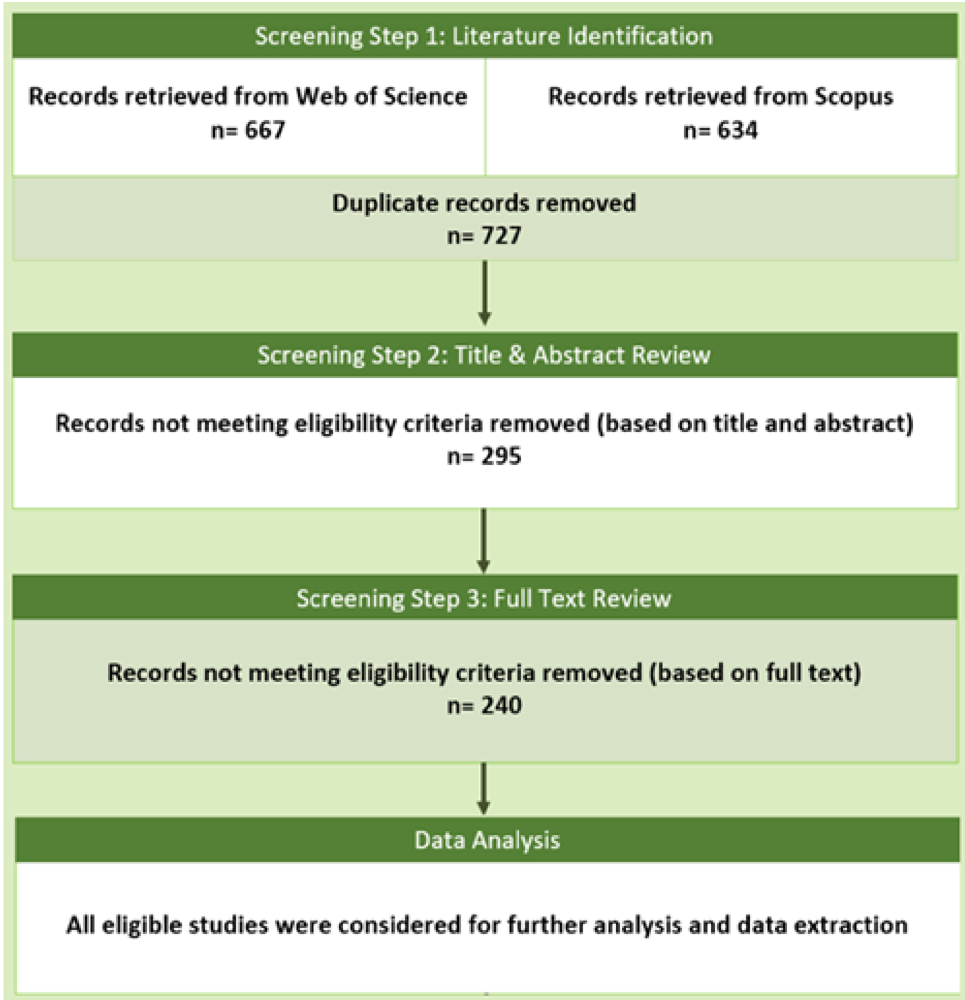

Figure 1. Flow chart of the screening steps in the quick scoping review, and the number of records considered eligible at each step.

Screening Step 1- Identification of Literature

To establish basic interest in the topic, a primary structured search was conducted through the online search engine Google Scholar (after Bermejo et al., 2022). Prior review of relevant literature was used to form six primary key words (macroalga*, seaweed*, aquaculture, offshore, wind, farm*) and 14 secondary key words (turbine, energy, climate change, ecosystem service*, cultivation, risk*, challenge*, benefit*, policy, carbon sequestration, blue economy, sustainability, multi-use, impact*) that were searched in Google Scholar, where the asterisk indicates a truncation wildcard (i.e., farm* yields results for farms, farming, farmer, and farmed). This resulted in 98 search results.

To broaden the search results, a more structured literature search was carried out using two reputable scientific databases: Web of Science and Scopus (after Bermejo et al., 2022). First, 8 key search terms were formulated using the verbiage from the initial research questions (see Introduction). Quotation marks were used for a combination search to reduce the number of irrelevant search results. Using the primary and secondary search terms, the following search combinations were used: “seaweed aquaculture”; “seaweed farm*”; “macroalga* aquaculture”; “offshore wind” AND seaweed AND aquaculture; “offshore wind” AND seaweed* AND farm*. The search of both databases was completed on 25 March 2023. Records from each search term were exported from the scientific databases into EndNote, a reference management software, containing bibliography type, author, title, DoI, publication year, and abstract. Duplicate records were removed first using the duplication function in EndNote’s software and subsequently through manual screening, which resulted in a total of 727 records (**Table 1**).

Table 1. Results of literature search of eight key search terms in Web of Science and Scopus databases on 25 March 2023. EndNote software and subsequent manual screening were used to remove duplicate records, resulting in 727 records for review.

Search Term	SCOPUS Results	Web of Science Results
"seaweed aquaculture"	187	297
"seaweed farm*"	384	303
"macroalga* aquaculture"	19	16
"macroalga* farm*"	21	19
"offshore wind" AND seaweed AND aquaculture	8	11
"offshore wind" AND seaweed AND farm*	9	11
"offshore wind" AND macroalga* AND aquaculture	2	4
"offshore wind" AND macroalga* AND farm*	4	6
Total without removing duplicates	634	667
Total after removing duplicates within a database	560	593
Total after removing duplicates between databases	727	

Screening Step 2- Title and Abstract Review

The 727 records deemed eligible in Screening Step 1 were sorted and screened against formal inclusion and exclusion criteria to determine eligibility for data analysis (**Table 2**). It is important to note that this study is focused on seaweed farming and not the production or products of natural seaweed biomasses, such as natural kelp beds, which is reflected in the eligibility criteria. The title and abstract of each record were reviewed against the eligibility criteria, identifying 296 records eligible to be assessed in Screening Step 3.

Table 2. Summary of the Exclusion and Inclusion criteria used in Phase 1 (literature identification), Phase 2 (title and abstract review), and Phase 3 (full text review) of the Quick Scoping Review to determine eligibility for this study.

Exclusion	Inclusion
Screening Step 1: Literature Identification	
Non-English	English
Before 2000 or after 03/2023	Between 01/2000-03/2023
Non-original articles	Peer-reviewed original articles
Not available on WoS or Scopus	Available in WoS or Scopus
Screening Step 2: Title and Abstract and Screening Step 3: Full Text	
No seaweed aquaculture	Seaweed Aquaculture
Exclusively laboratory studies	Reviews, models, field studies at aquaculture sites, surveys
Focus on optimization of cultivation or post-harvest techniques	Focus on ecosystem services
Focus on biological functions of seaweed	Focus on spatial and temporal assessment of seaweed aquaculture
Description of biodiversity associated with seaweed aquaculture	Description of biotic interplay related to seaweed aquaculture
Weak link to seaweed aquaculture	Assessment of socio-economic values of seaweed aquaculture

Screening Step 3- Full Text Review

The 295 records deemed eligible in Screening Step 2 were then reviewed against the same eligibility criteria using the full text. In addition to not meeting inclusion criteria, 14 records could not be accessed for review and were therefore excluded. Full text review resulted in 240 eligible records that provided the base for data analysis.

Data Analysis

The 240 eligible records identified in Screening Step 3 were exported from EndNote into Excel, where they were randomly assigned a record number and mined for data. In Excel, columns were assigned the following data categories: 1) Year of Publication, 2) Location, 3) Scale of Study, 4) Study Protocol Type, 5) Species of Interest, 6) Aquaculture Type, 7) Farm Size, 8) Ecosystem Services, 9) Knowledge Gaps, 10) Constraints, 11) Negative Impacts/Trade-offs, 12) Multi-use, and 13) Author's Notes. Following the subcategories listed in **Table A1** (see

Appendix), the full text of each record was reviewed, and information related to each category was recorded.

For the "Constraints" category, key terminology was used to identify factors that inhibit the successful implementation or management of seaweed cultivation. Terminology used for constraint identification includes constraint, challenge, bottleneck, problem, obstacle, barrier, and restriction.

Studies with particular interest in seaweed multi-use projects were separately categorized. Records were qualified as offshore wind-focused if the primary objective of the study was related to seaweed farm-offshore wind multi-use or if an entire section of the study was focused on seaweed farm-offshore wind multi-use.

To determine whether the emphasis on the various ecosystem services, constraints, and knowledge gaps varied between all of the seaweed farming literature versus the literature that focused specifically on seaweed farm-offshore wind multi-use, we used chi-square analyses. For example, we tested for a difference in the distribution of records among Provisioning vs. Regulating/Habitat vs. Cultural Services subcategories within the "Ecosystem Services" category between all literature versus the offshore wind-focused literature, and so forth for other categories of interest.

RESULTS

Identification of Potential Species for Cultivation

From WOA2018, mean (± SD) temperature near the proposed Ocean Wind 1 leasing area was: 4.19 ± 1.31°C (winter), 10.62 ± 2.93°C (spring), 18.42 ± 2.94°C (summer), and 14.47 ± 2.87°C (fall). The environmental growth requirements of *S. latissima* are 5–20°C (Egan and

Yarish 1988; Filbee-Dexter et al. 2016; Kerrison et al., 2015), which overlap with the ambient temperatures in spring, summer, and fall. The environmental growth requirements of *F. vesiculosus* are 15–20°C (Graiff et al. 2015; Nygård and Dring 2008), which overlap most closely with the ambient temperatures in summer (**Figure 2a**).

The mean (± SD) salinity was: 32.15 ± 0.70 psu (winter), 31.89 ± 0.75 psu (spring), 31.65 ± 0.58 psu (summer), and 32.19 ± 0.33 psu (fall). The environmental growth requirements of *S. latissima* are 28–34 psu (Kerrison et al., 2015; Yarish et al. 2017), which overlap with the ambient salinity in all four seasons. The environmental growth requirements of *F. vesiculosus* are 10–35 psu (Nygård and Dring 2008), which overlap with the ambient salinity in all four seasons (**Figure 2b**).

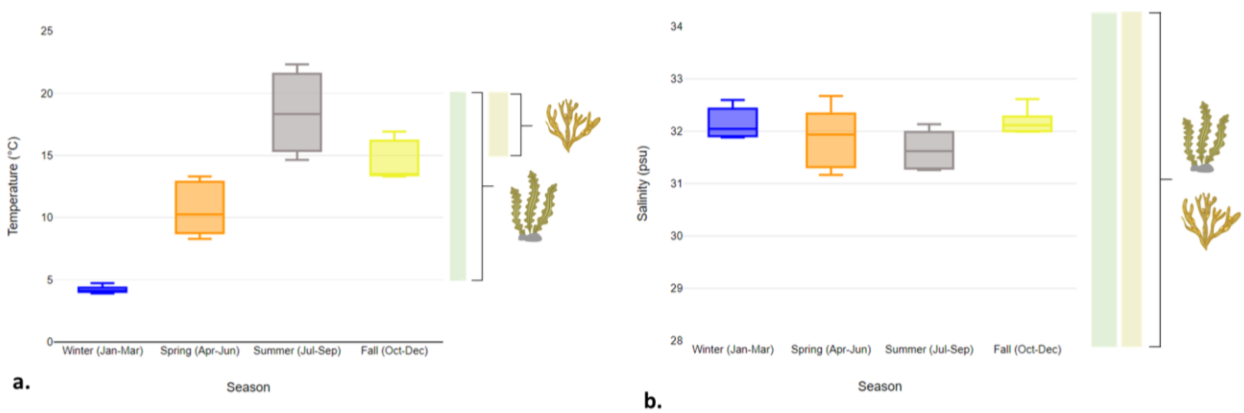

Figure 2. Environmental growth requirements of *S. latissima* (green bars) and *F. vesiculosus* (yellow bars) against ambient seasonal temperature (°C) (**a**) and salinity (psu) (**b**) near the proposed Ocean Wind 1 leasing area in New Jersey. Growth requirements were identified through a literature search and oceanographic data are from World Ocean Atlas 2018 Data Access (WOA2018).

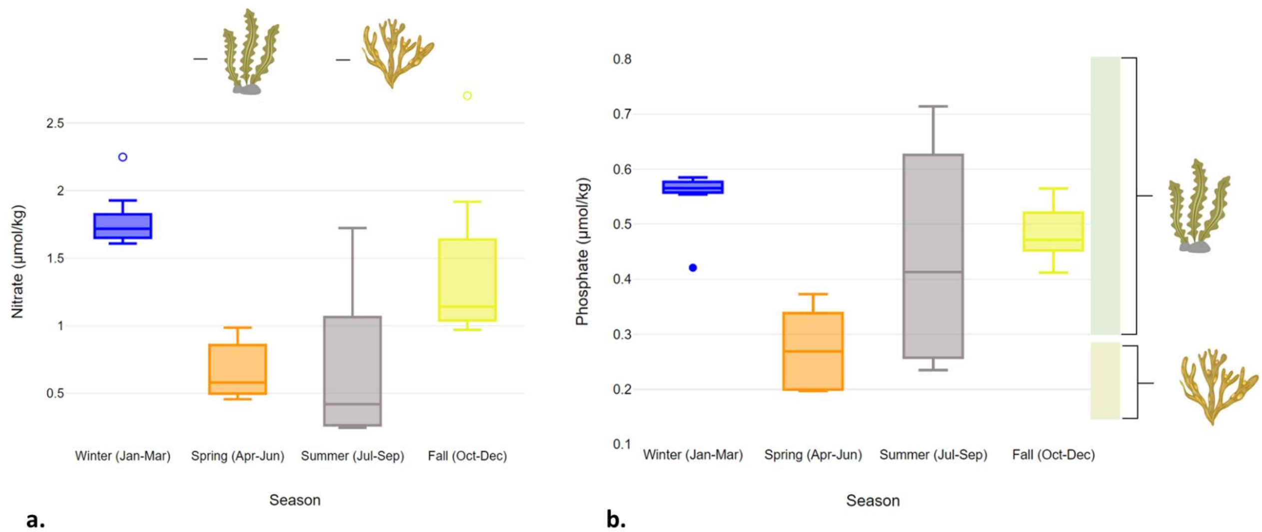

Figure 3. Environmental growth requirements of *S. latissima* (green bars) and *F. vesiculosus* (yellow bars) against ambient seasonal nitrate (µmol/kg) (**a**) and phosphate (µmol/kg) (**b**) concentrations near the proposed Ocean Wind 1 leasing area in New Jersey. Environmental growth requirements were identified through a literature search and oceanographic data are from World Ocean Atlas 2018 Data Access (WOA2018). Growth requirements for the nitrate are above the graphed area for both species (*S. latissima*: 10–30 µmol/kg, and *F. vesiculosus*: 48 µmol/kg).

The mean (± SD) nitrate concentration was: 1.78 ± 1.14 µmol/kg (winter), 0.66 ± 0.70 µmol/kg (spring), 0.68 ± 0.56 µmol/kg (summer), and 1.41 ± 1.19 µmol/kg (fall). The environmental growth requirements of *S. latissima* are 10–30 µmol/kg (Kerrison et al., 2015; Wheeler and Weidner, 1983; Yarish et al. 2017), which are considerably higher than the ambient nitrate concentration in any season. The environmental growth requirement of *F. vesiculosus* is around 48 µmol/kg (Pedersen et al., 1997), which also exceeds the ambient nitrate concentration across all seasons (**Figure 3a**).

The mean (± SD) phosphate concentration was: 0.55 ± 0.21 µmol/kg (winter), 0.27 ± 0.19 µmol/kg (spring), 0.44 ± 0.29 µmol/kg (summer), and 0.48 ± 0.20 µmol/kg (fall). The environmental growth requirement of *S. latissima* is ≥ 0.30 µmol/kg (Kerrison et al., 2015), which overlaps with the ambient phosphate concentration in winter and fall. The environmental growth requirements of *F. vesiculosus* are 0.13–0.28 µmol/kg (Pedersen et al., 2010), which overlap with the ambient phosphate concentration in spring (**Figure 3b**).

Quick Scoping Review

Overview of Records: Date of Publication and Location

There is an increasing trend of eligible records from the year 2000 to 2023 (**Figure 4**). In 2022 alone, 56 eligible records were published. A noticeable decline in the trend in 2023 is due to the search being completed in March of 2023, therefore all records published afterwards were not considered. The primary geographic locations of eligible studies were in Asia (37.9%), Europe (19.2%), and globally (17.1%) (**Figure 5**). Only 14 (5.8%) eligible articles were focused on North America, all of which were focused on the USA across Maine, New York, and California. In the records that focused on the co-location of seaweed farming with offshore wind energy, the majority of the records were in Europe (76.9%), with the remaining records highlighting Asia, Africa, and globally.

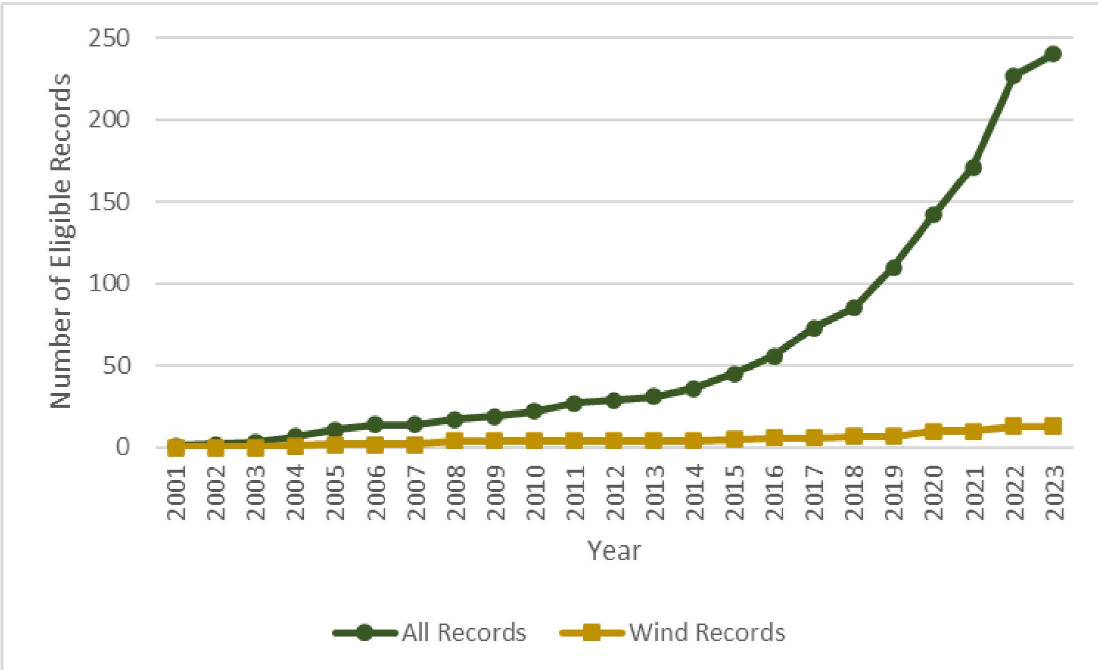

Figure 4. The number of eligible records for all literature records (“All Records”) and the offshore wind-focused records (“Wind Records”) in the Quick Scoping Review sorted by year of publication. Data points for the year 2023 only consider records published in January–March.

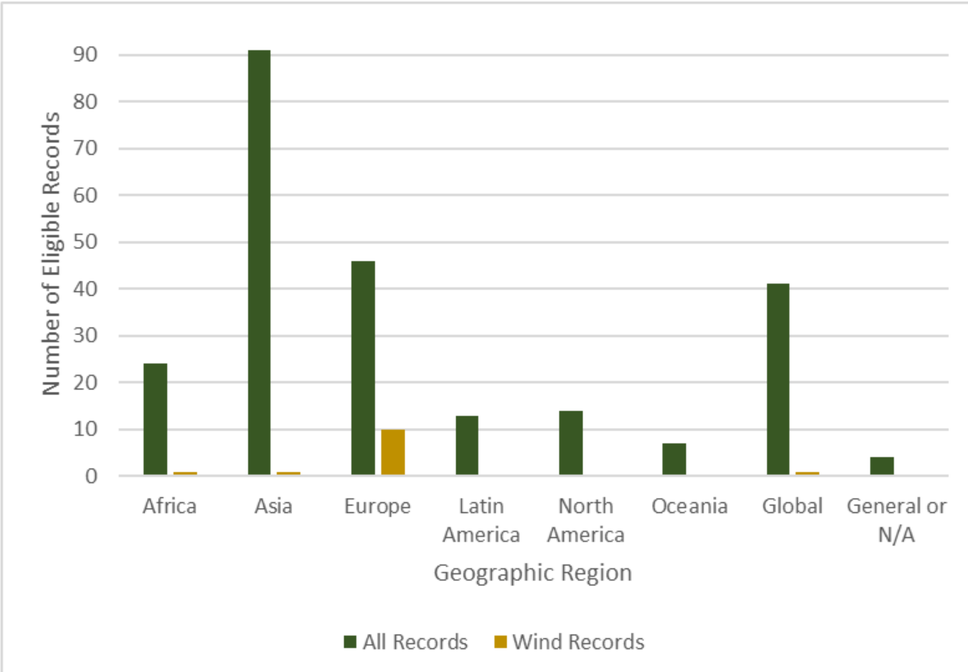

Figure 5. The number of eligible records for all literature records ("All Records") and the offshore wind-focused records ("Wind Records") in the Quick Scoping Review sorted by geographic region.

Half (50.8%) of the eligible articles were conducted on a local scale, focusing data collection on cities, villages, individual farming locations, or a small portion of one country. The other half of the studies were conducted on a national (22.9%), global (15.8%), regional (6.7%), or continental scale (3.8%).

Cultivated Species

More than half of all 240 records (66.3%) identified a total of 75 seaweed species or taxonomic groups for seaweed cultivation. The species or broader taxonomic groups identified were distributed across the red seaweeds (phylum Rhodophyta: 44.4% of records), brown seaweeds including kelps (phylum Ochrophyta: 24.8% of records), and green seaweeds (Phylum

Chlorophyta: 7.5% of records). A “General” subcategory was used for records that referred to seaweed cultivation in a general sense, referenced many species, or did not identify any seaweed species of interest (23.3%).

The most commonly cited genus of brown seaweed was *Saccharina* (40.7%), including *Saccharina japonica* and *Saccharina latissima*. The two most commonly cited genera of red seaweed were *Kappaphycus* (33.1%) and *Eucheuma* (25.9%). The most commonly cited genus of green seaweed was *Ulva* (53.8%), including *Ulva intestinalis*, *Ulva lactuca*, *Ulva prolifera*, and *Ulva rigida*.

In total, six different species were cited in the records that focus on the co-location of seaweed farming with offshore wind. These species include: *Saccharina latissima* (46.2%), *Laminaria digitata* (15.9%), *Palmaria palmata* (15.9%), *Kappaphycus alvarezii* (7.7%), *Euchema denticulatum* (7.7%), and *Ulva lactuca* (7.7%). Overall, brown seaweed species were identified the most in conjunction with offshore wind (61.5%).

Cultivated species differed regionally (**Table 3**). In records focusing on Asian countries, 20 seaweed species or taxonomic groups were cited with *Kappaphycus* spp. cited most frequently (21.8%), followed closely by *Eucheuma* spp. (16.1%) and *Gracilaria* spp. (15.3%). In the records focusing on European and North American countries, *Saccharina latissima* was the most cited species (56.4% and 50.0%, respectively). *Laminaria* spp. were the second most cited species in European records (18.0%) (however, note that the genera *Laminaria* and *Saccharina* may be synonymous in some cases) and *Gracilaria tikvahiae* was the second most cited species in North American records (25.0%).

Table 3. Percent contribution of each taxonomic group of seaweed per geographic region identified in the Quick Scoping Review: Africa (n=35), Asia (n=124), Europe (n=39), Latin America (n=10), North America (n=12), and Oceania (n=10). "-" indicates no available data for a taxonomic group in the given region.

	Geographic Region					
Species	Africa	Asia	Europe	Latin America	North America	Oceania
Acanthophora spicifera	-	0.81	-	-	-	-
Alaria esculenta	-	-	5.13	-	-	-
Asparagopsis spp.	-	-	5.13	-	-	-
Caulerpa spp.	2.86	1.61	-	-	-	10.00
Chondracanthus chamissoi	-	-	-	10.00	-	-
Cladosiphon spp.	-	0.81	-	-	-	10.00
Durvillaea spp.	-	-	-	-	-	20.00
Ecklonia radiata	-	-	-	-	-	10.00
Enteromorpha prolifera	-	0.81	-	-	-	-
Euchema spp.	42.86	16.13	-	-	8.33	-
Fucus vesiculosus	-	-	2.56	-	-	-
Furcellaria lumbricalis,	-	-	2.56	-	-	-
Gelidiella acerosa	-	0.81	-	-	-	-
Gracilaria spp.	-	15.32	-	20.00	25.00	-
Halimeda spp.	2.86	-	-	-	-	-
Halymenia spp.	-	-	-	-	-	10.00
Hizikia fusiforme	-	0.81	-	-	-	-
Hydropuntia edulis	-	0.81	-	-	-	-
Hypnea spp.	-	1.61	-	10.00	-	-
Kappaphycus spp.	45.71	21.77	-	30.00	-	10.00
Laminaria spp.	-	4.84	17.95	-	-	-
Lessonia corrugata	-	-	-	-	-	10.00
Macrocystis pyrifera	-	-	-	10.00	8.33	10.00
Palmaria palmata	-	-	5.13	-	-	-
Porphyra/Pyropia spp.	-	11.29	-	10.00	-	-
Saccharina spp.	-	5.65	56.41	10.00	50.00	-
Sarcodia suae	-	0.81	-	-	-	-
Sargassum spp.	-	3.23	-	-	8.33	-
Turbinaria conoides	-	0.81	-	-	-	-
Ulva spp.	2.86	7.26	5.13	-	-	-
Undaria spp.	-	4.84	-	-	-	10.00
Valonia spp.	2.86	-	-	-	-	-

Multi-Use

Of the 240 eligible records, only 134 (55.8%) mentioned the use of seaweed farming with other ocean use activities, and 13 (5.4%) records had a strong focus on the co-location of seaweed farming with offshore wind energy. Within the 134 records that mentioned seaweed farming multi-use, the majority (77.6%) referred to seaweed use in Integrated Multi Trophic Aquaculture (IMTA) while the others referred to seaweed farming co-located with offshore wind energy (21.6%) or wave energy (0.7%).

Ecosystem Services

The QSR resulted in 210 records identifying ecosystem services of seaweed farming. Some studies provided evidence for more than one ecosystem service. Across all records, “Provisioning” services were identified the most (42.5%) followed by “Regulating and Habitat” services (34.3%) and “Cultural” services (23.3%) (**Figure 6a**). In the records that focused on the co-location of seaweed farming with offshore wind energy, the vast majority of services identified were “Provisioning” services (70.0%) with “Regulating and Habitat” (25.0%) and “Cultural” services (5.0%) appearing less frequently (**Figure 6b**). There was a significant difference in the distribution of records between all records and the offshore wind-focused records across Provisioning versus Regulating/Habitat versus Cultural services ($\chi2 = 12.7$, df = 2, $p = 0.027$) (**Figure 6**).

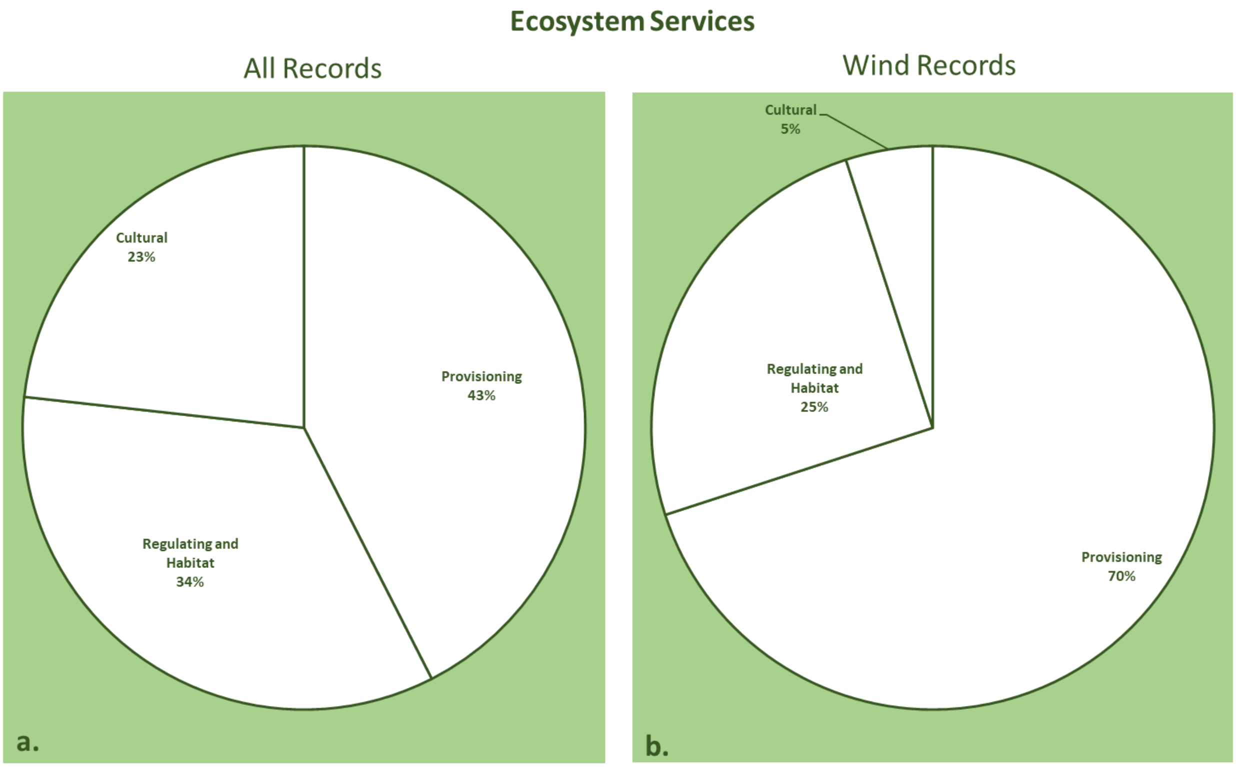

Figure 6. Ecosystem services identified in all literature records ("All Records"; n=240) **(a)** and in the offshore wind-focused records ("Wind Records"; n=13) **(b)** in the Quick Scoping Review, including provisioning, regulating and habitat, and cultural services.

Provisioning Services

Within the "Provisioning" services category, the service of seaweed farms most commonly identified was the use of seaweed as food or food additives for human consumption (23.9%). Human consumption was followed closely by fodder and fertilizer in the agriculture industry (17.1%) and raw chemicals such as agar and hydrocolloids (15.7%). Other provisioning services of cultivated seaweed included feedstock for biofuel (13.0%) or in medicinal (12.6%) and cosmetic (11.5%) products (**Figure 7a**).

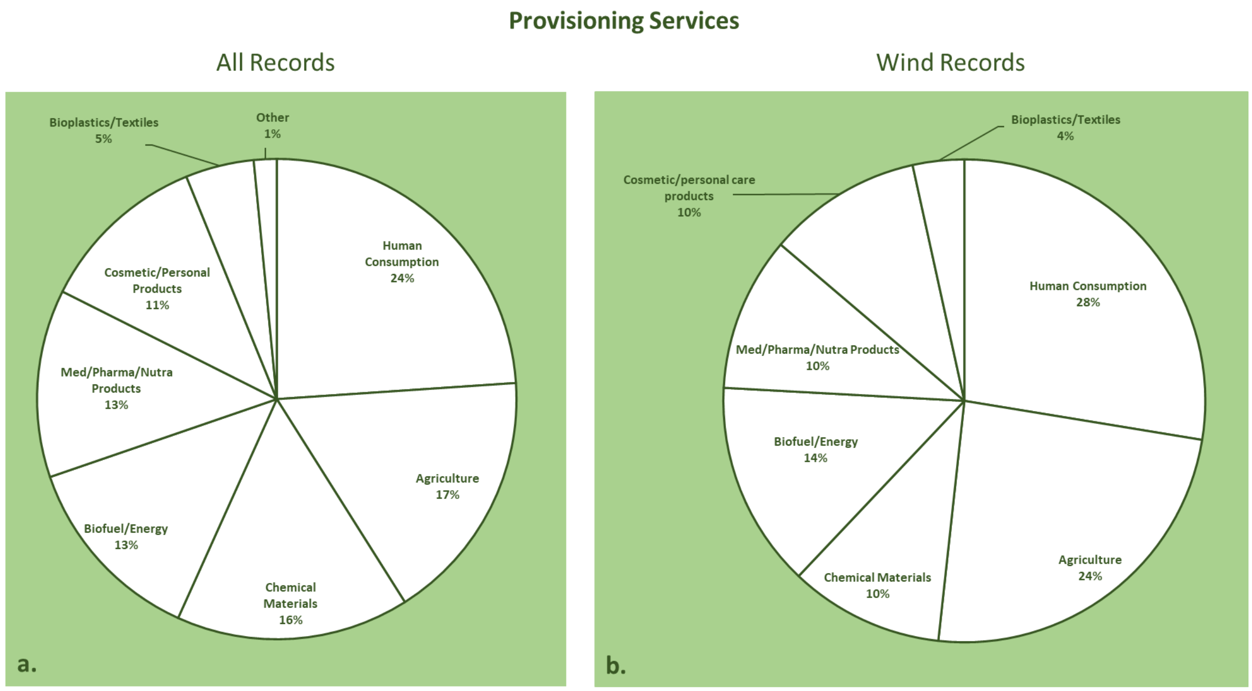

Figure 7. Provisioning ecosystem services identified in all literature records ("All Records"; n=240) **(a)** and in the offshore wind-focused records ("Wind Records"; n=13) **(b)** in the Quick Scoping Review.

In the records that focused on the co-location of seaweed farming with offshore wind energy, the two most identified provisioning services were still human consumption (27.6%) and agricultural products (24.1%), but the third most identified service was the use of seaweed as feedstock for biofuel (13.8%) (**Figure 7b**). Yet, there was no statistically significant difference in the distribution of records between all records and the offshore wind-focused records within the Provisioning services ($\chi 2 = 1.7$, df = 6, p = 0.947) (**Figure 7**).

Regulating and Habitat Services

Within the "Regulating and Habitat" services category, seaweed's potential for bioremediation and absorption of excess nutrients was the most identified service (23.3%) followed by nutrient sequestration (15.5%) and habitat/food provisioning for marine life

(12.9%). Other regulating services of seaweed farming included carbon offsetting (7.3%), buffering of ocean acidification (7.1%), climate change mitigation (6.8%), and coastal protection (5.8%) (**Figure 8a**).

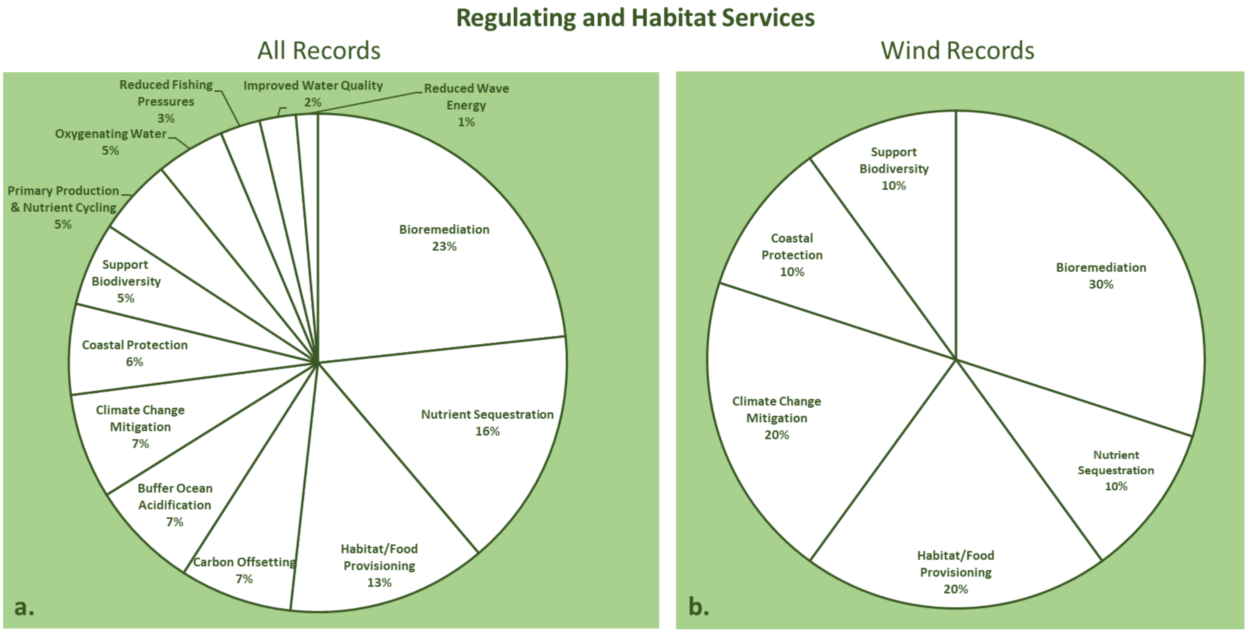

Figure 8. Regulating and habitat ecosystem services identified in all literature records ("All Records"; n=240) **(a)** and in the offshore wind-focused records ("Wind Records"; n=13) **(b)** in the Quick Scoping Review.

In the records that focus on the co-location of seaweed farming with offshore wind energy, bioremediation was also the most identified regulating and habitat service (30.0%) with climate change mitigation (20.0%) and habitat/food provisioning (20.0%) identified second and third most (**Figure 8b**). There was no statistically significant difference in the distribution of records between all records and the offshore wind-focused records within the Regulating and Habitat services ($\chi 2 = 6.5$, df = 12, $p = 0.892$) (**Figure 8**).

Cultural Services

Within the "Cultural" services category, the source of income and employment provided by seaweed farming (30.1%) was the service identified the most followed closely by the ability for seaweed farming to improve the quality of life for coastal communities (26.9%) and empower women (15.0%). Other cultural services provided by seaweed farming identified through the QSR were the diversification of livelihoods for coastal communities (5.7%), global food security (5.2%), alleviation of poverty (4.7%), and economic growth of coastal communities (4.2%) (**Figure 9a**).

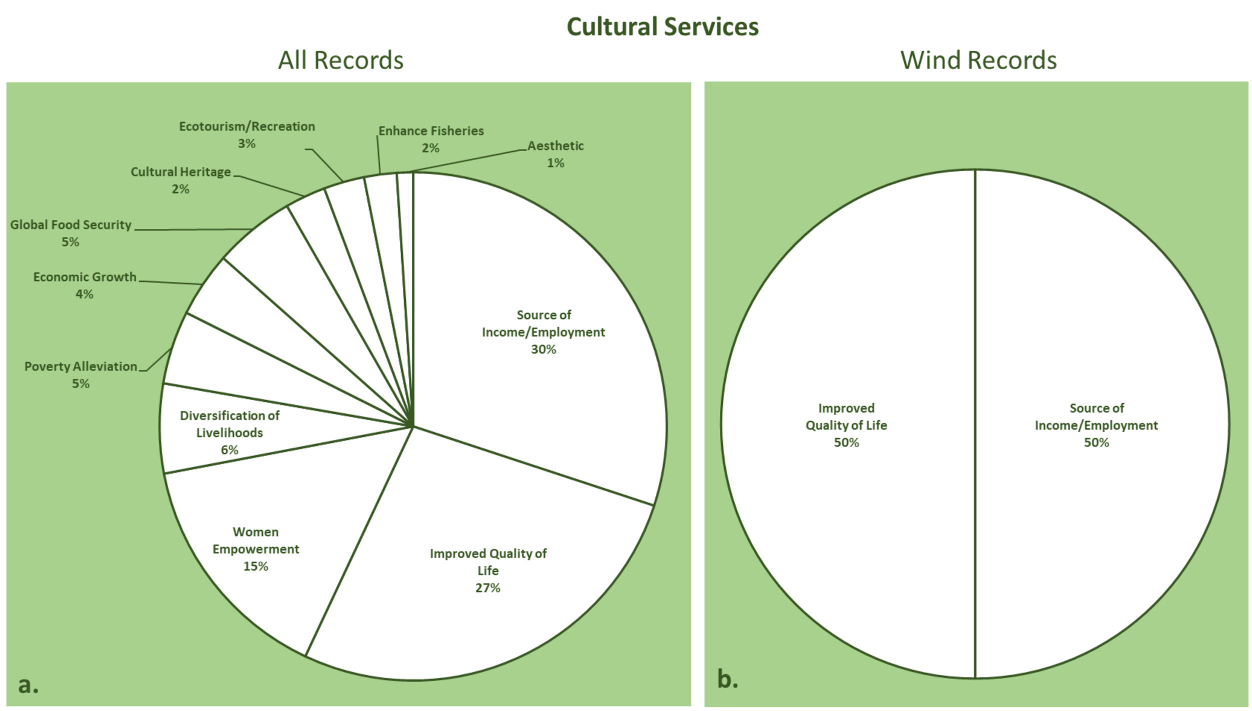

Figure 9. Cultural ecosystem services identified in all literature records ("All Records"; n=240) **(a)** and in the offshore wind-focused records ("Wind Records"; n=13) **(b)** in the Quick Scoping Review.

In the records that focus on the co-location of seaweed farming with offshore wind energy, only two cultural services were identified: source of income and employment (50.0%) and the ability of seaweed farming to improve the quality of life for coastal communities (50.0%)

(**Figure 9b**). There was no statistically significant difference in the distribution of records between all records and the offshore wind records within the Cultural services ($\chi2 = 1.5$, $df = 10$, $p = 0.999$) (**Figure 9**).

Constraints

Of the 240 records reviewed, 181 records (75.4%) identified constraints in seaweed farming. Constraints were categorized using the PESTEL analysis framework (**Figure 10a**), identifying them as either political, environmental, social, technical, economic, or legal (Yüksel, 2012; after Bermejo et al., 2022). An additional category ("Study Design") was added for records that identified constraints in the design or execution of its own study. For example, modeling frameworks having limited data availability or survey studies having a potentially biased survey population. Each category was further divided into subcategories, summarized in **Table A3** (see Appendix).

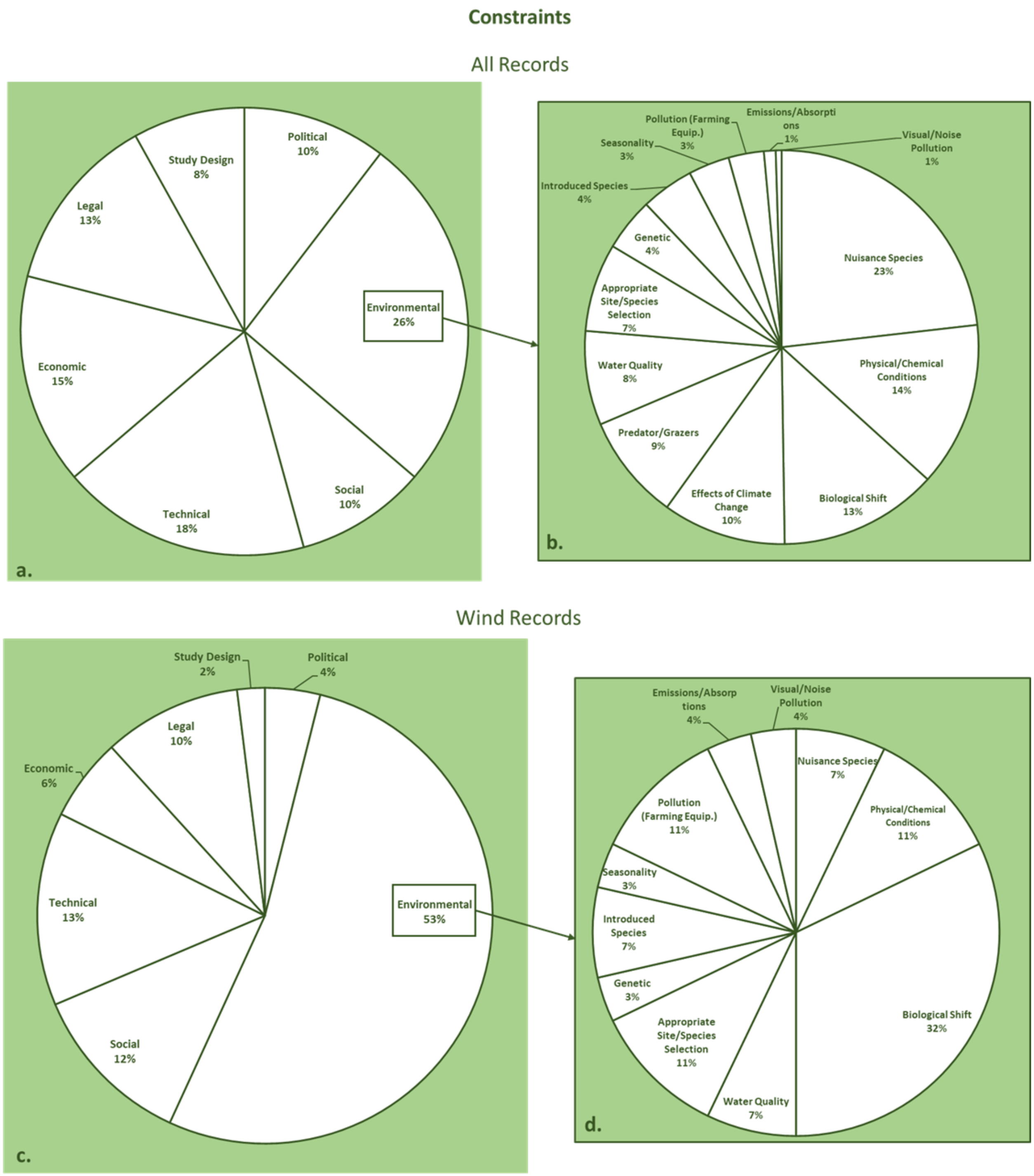

Figure 10. Overview of the constraints identified in all literature records ("All Records"; n=240) **(a)** and in the offshore wind-focused records ("Wind Records"; n=13) **(c)** and the specific Environmental constraints identified in all records **(b)** and in the offshore wind-focused records **(d)** in the Quick Scoping Review.

The constraint category that was identified the most in the QSR was “Environmental” (25.9%), which was cited by 112 records. The most cited “Environmental” constraint was the presence of nuisance species, such as pests, diseases, or epiphytes (23.2%) which leads to a decrease in crop yield (**Figure 10b**). The physical and chemical ocean conditions also pose a threat to farm productivity (13.5%), particularly at sites where the wind and currents are strong, severe weather is frequent, and nutrient availability is limited. Biological shift, or changes to the local ecosystem, was the third most cited “Environmental” constraint cited in the QSR (13.0%). Concerns related to the effects of climate change (10.1%), predators and grazers decreasing seaweed biomass (8.7%), and reduced water quality (7.7%) were also cited as constraints. Other “Environmental” constraints identified included appropriate species and site selection (7.2%), genetic pollution from crop to wild species (4.3%), introduced non-native species (4.3%), the seasonality of seaweed farming (3.4%), pollution from farming equipment (2.9%), the emission/absorption of halocarbon containing gasses (0.9%), and visual pollution (0.5%).

The constraint category that was identified the second most was “Technical” (18.0%), which was cited by 78 records. The “Technical” constraint that was cited the most was the barriers to technology (27.1%), largely for offshore operations or for creating innovative farming equipment. Constraints at the nursery level was cited the second most (23.6%), related to breeding techniques and the improvement of seed strain quality. Constraints related to harvesting techniques and equipment (17.1%) as well as the need for training and education of farmers (11.4%) were cited. Other “Technical” constraints identified through the QSR included post-harvest handling (9.3%), appropriate selection of species and farm location (5.0%), production (4.3%), hazards (1.4%), and the impacts of global climate change (0.7%).

"Economic" constraints were the third most (15.2%) identified category of constraints, with 66 records identifying "Economic" constraints of seaweed farming. The most cited "Economic" constraint was the costs associated with the investment, production and management of seaweed farms (29.4%). For coastal communities reliant on seaweed farming as a source of employment, low-income generation from seaweed farming was cited as a major constraint (9.4%). The financial feasibility of seaweed production was also cited as a constraint (4.7%), as the high cost of production may not be met by the low prices of seaweed products. Similarly, constraints related to the market were cited so frequently they had to be further divided into three subcategories: low value or market viability of seaweed products (27.1%), the volatile seaweed market (18.8%), and the underdevelopment of the seaweed market (5.9%).

"Legal" constraints were the fourth most (12.9%) identified category, in which 56 records identified five main constraints. The primary constraint cited through the QSR was the governance of seaweed farming (49.3%), more specifically the lack of seaweed specific policy or regulatory frameworks. Biosecurity regulation was also of concern (18.8%), to best deal with the pest organisms that threaten crop yield. The third most cited constraint was related to food safety (15.9%) and the lack of protocols to maintain and measure the safety of seaweed grown for human consumption. Constraints related to licensing and permitting of seaweed farming areas (11.6%) and spatial planning (4.3%) were also cited.

The QSR found that "Political" (10.4%), "Social" (9.5%), and "Study design" (8.1%) constraints were cited the least. Through 45 records, two "Political" constraints were identified: conflicts with other ocean use activities (69.6%) and lack of governmental support (30.4%). "Social" constraints were cited in 41 records, where the primary constraint was a negative public opinion or lack of public support (28.0%). Occupational health hazards to farmers (20.0%) and lack of stakeholder engagement (20.0%) were also commonly cited. Other "Social" constraints identified in the QSR are gender inequalities (16.0%), visual impact (10.0%), and job conflicts (6.0%). There were 35 records that self-identified "Study Design" constraints, where study limitations ranged from limited data availability (42.9%), limitations to model design (31.4%), and a study population that was biased or not representative (8.6%).

All 13 of the records that focus on the co-location of seaweed farming with offshore wind energy cited constraints related to seaweed farming, and "Environmental" constraints were cited the most (52.9%) (**Figure 10c**). Within these records, the most commonly cited constraint was changes to the local ecosystem (32.1%) by way of competition with local communities, dangers to marine mammals and birds, and reduced primary production (**Figure 10d**). The second most cited constraint category was "Technical" (13.7%), where the need for improved technology required for offshore infrastructure was cited the most (42.9%), followed closely by "Social" (11.8%), where stakeholder perception or conflicts were cited the most (33.3%). There was a significant difference in the distribution of records between all records and the offshore wind-focused records within the Constraints categories ($\chi 2 = 19.8$, df = 6, $p = 0.003$) (**Figure 10a,c**). Within the Environmental Constraints subcategory, there was also a significant difference in the distribution of records between all records and the offshore wind records ($\chi 2 = 23.1$, df = 12, $p = 0.027$) (**Figure 10b,d**).

Knowledge Gaps

From the 240 records analyzed, 131 (54.6%) identified knowledge gaps related to the field of seaweed farming. Knowledge gaps were also categorized using the PESTEL analysis framework (**Figure 11a**), identifying gaps as either political, environmental, social, technical, economic, or legal (Yüksel, 2012). Each category was further divided into subcategories, summarized in **Table A4** (see Appendix).

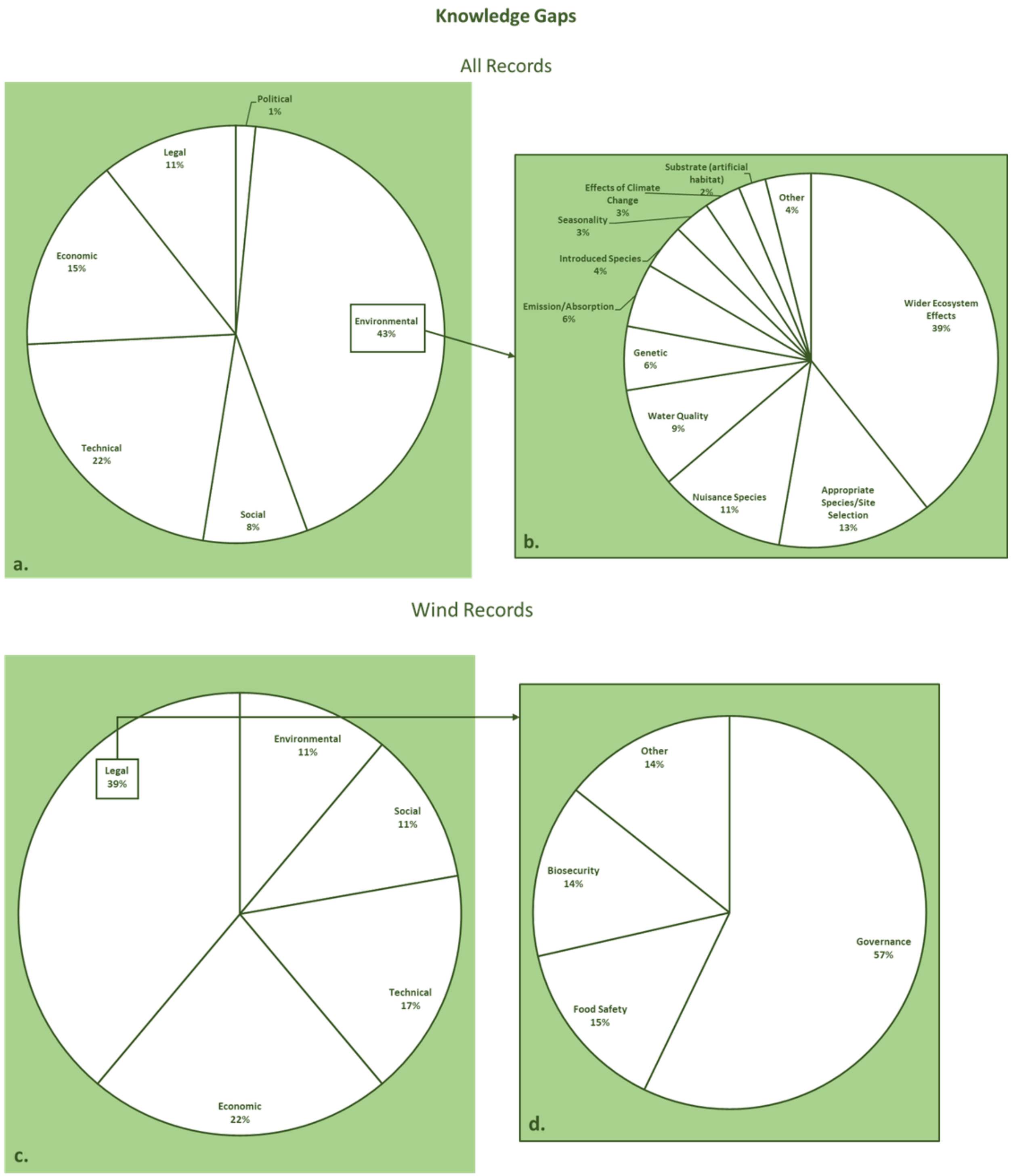

Figure 11. Overview of the knowledge gaps identified in all literature records ("All Records"; n=240) **(a)** and in the offshore wind-focused records ("Wind Records"; n=13) (**c**) and the specific Environmental knowledge gaps identified in all records **(c)** and specific Legal knowledge gaps identified in the wind records (**d**) in the Quick Scoping Review.

The knowledge gap category that was identified the most in the QSR was "Environmental" (42.9%) (**Figure 11b**). In total, 85 records cited "Environmental" knowledge gaps, most of them concerning the wider ecosystem effects of seaweed farming (39.4%). Wider ecosystem effects included competition with local algae species, impacts on fish recruitment and fishery biomass, potential impacts to marine megafauna and seabirds, and impacts on benthic communities with regard to competition, shading, and sedimentation. Unknown criteria for proper species and site selection was the second most cited "Environmental" knowledge gap (13.4%) followed by the impacts of nuisance species, such as pests, diseases, and epiphytes (11.0%). Other "Environmental" knowledge gaps included the impact on water quality (8.7%), consequences of genetic mixing of cultivated species with native species (5.5%), the emission of halocarbon containing gasses and contribution to the carbon cycle (5.5%), and the introduction of nonnative species (3.9%).

"Technical" knowledge gaps were the second most identified category (21.7%), which were identified from 43 records. Most of the "Technical" knowledge gaps cited were related to the nursery processes (31.4%) of seaweed farming, such as species-specific data on breeding or how to improve the quality of seed strain to withstand increasing ocean temperatures and resist diseases. Technical gaps related to production (25.5%) were also cited, including methods to increase seaweed biomass, methods to increase stocking density, and the feasibility of scaling up aquaculture productions. Gaps in technology (25.5%) were also cited, with regards to the infrastructure needed for offshore vs nearshore cultivation and the innovation required to build sustainable, long-lasting infrastructure. Other "Technical" knowledge gaps included species selection (9.8%), product quality (3.9%), harvesting practices (2.0%), and post-harvest handling practices (2.0%).

"Economic" knowledge gaps were the third most identified category (15.2%), which were identified by 30 records. The majority of "Economic" knowledge gaps cited concerned the unknown market value and viability of seaweed products (45.7%). The unknown costs of labor, installation, and operations related to seaweed farming (28.6%) were also identified as knowledge gaps. Other "Economic" knowledge gaps were identified as the need for life cycle assessments (14.3%), financial feasibility (8.6%), and integration of economic and technical factors of seaweed farming (2.9%).

All other knowledge gap categories were cited far less, with 10.6% being "Legal" gaps, 8.1% being "Social" gaps, and 1.5% being "Political" gaps. The "Legal" knowledge gaps cited primarily concerned the governance/management of seaweed farms (42.3%), need for improved biosecurity practices (30.8%), and unclear regulatory framework of food security with regards to seaweeds grown for human consumption (23.1%). The "Social" knowledge gaps identified through the QSR had a fairly even distribution of concern for how to improve gender inequalities in farming practices (18.8%), lack of support for farmers (18.8%), and an overall lack of census data to track previous years of seaweed farming (18.8%). Other "Social" knowledge gaps include occupational health hazards (12.5%) and uncertainty about public opinion of seaweed farming (12.5%). Finally, few "Political" knowledge gaps were cited, but lack of governmental support, need for access benefit sharing analysis, and potential interaction with fisheries were identified equally.

In the records that focused on the co-location of seaweed farms with offshore wind energy, only half (46.2%) identified knowledge gaps related to seaweed farming. As opposed to the knowledge gaps identified by all records, these records cited "Legal" knowledge gaps the most (38.9%), followed by "Economic" gaps (22.2%) and "Technical" gaps (16.7%) (**Figure 11c**).

The "Legal" knowledge gap cited the most amongst these records was the governance of a multi-use site with regards to marine spatial planning and reduced competition with other ocean use activities (57.1%) (**Figure 11d**). Furthermore, the most cited "Economic" knowledge gap was the market value and viability of seaweed products (60.0%). There was a significant difference in the distribution of records between all records and the offshore wind records within the Knowledge Gaps categories ($\chi 2 = 15.5$, df = 5, $p = 0.008$) (**Figure 11a,c**).

DISCUSSION

Offshore Seaweed Farming in New Jersey?

In order to determine if seaweed farm-offshore wind co-location is feasible in New Jersey, it is first necessary to identify commercially valuable seaweed species suitable for offshore cultivation. Based on an examination of species' environmental growth requirements and *in situ* oceanographic conditions, *S. latissima* and *F. vesiculosus* appear to be unsuitable for cultivation under ambient conditions at a proposed offshore wind energy leasing area in New Jersey (Ocean Wind 1) due to insufficient nutrients. The nitrate levels at the proposed lease were well under the requirements for growth of both *S. latissima* and *F. vesiculosus*, identifying ambient nitrate as the limiting resource. This finding is consistent with previous research, as the growth of natural seaweed beds is most commonly limited by nitrogen availability followed by phosphorus availability (Roleda and Hurd, 2019). Cultivation of seaweed at offshore wind sites may therefore require advanced cultivation technology to artificially enhance nutrient levels and meet the nutrient demand for seaweed growth. For example, preliminary sea trials have used a novel technology to artificially upwell nutrient rich waters at offshore seaweed farms (Fan et al., 2019). However, such technology could have unintended environmental ramifications that require consideration (UNEP, 2023). An alternative method involves engineering seaweed farms to mechanically transport seaweed biomass into deep water at night for nutrient absorption and to the surface during the day for light absorption; yet these technologies remain untested (NASEM, 2021).

Integrated Multi-Trophic Aquaculture (IMTA) also may increase nutrient availability for seaweed farming (Troell et al., 2009). In IMTA, complementary species of different trophic levels are cultivated together to maximize sustainability and efficiency of production–for example, seaweed growth alongside fed finfish aquaculture (Roleda and Hurd, 2019). In this scenario, nutrient-rich wastewater flows from the finfish to the seaweed, and the seaweed acts as a biofilter removing excess nutrients and converting them to usable biomass (Roleda and Hurd, 2019). Although only one commercial-scale offshore IMTA system currently exists, experimental offshore systems using seaweed species have been trialed in Germany, the USA, Norway, the Netherlands, France, the UK, and Israel (Buck et al., 2018). Further, IMTA and offshore wind farm multi-use has been trialed off the coast of South Korea and modeled in the German EEZ of the North Sea (Buck et al., 2018).

As compared to offshore waters, ambient nutrient availability tends to be higher in inshore waters, which are closer to land-based nutrient sources. Hence, at ambient conditions, the cultivation of *S. latissima* and *F. vesiculosus* may be best achieved with current technologies at inshore locations in New Jersey. However, the demand for coastal space also tends to be higher at inshore locations and this can yield spatial use conflicts with other activities like tourism, recreation, or aesthetic enjoyment due to the visual impact of farming equipment and activity

(UNEP, 2023). Co-location of seaweed farming within existing, carefully planned New Jersey aquaculture in an IMTA approach could help to alleviate such conflicts (Falconer et al., 2023).

Further research is required to determine the most suitable seaweed species with commercial value for cultivation in New Jersey. Our literature search yielded little information on the native seaweed species of New Jersey, highlighting a knowledge gap in New Jersey's marine ecosystem. A comprehensive list of New Jersey's native seaweeds and their environmental requirements for growth are needed to further identify cultivable species and advance the seaweed farming industry. In addition, ongoing changes in physicochemical oceanographic variables due to climate change require consideration in the context of seaweed farming in New Jersey.

Global Opportunities, Constraints and Gaps for Multi-Use

The QSR confirmed that interest in seaweed farming and its co-location with offshore wind is growing and relevant on a global scale. The comparison of data from all literature records with that from offshore wind-focused records highlights the unique opportunities and challenges of seaweed multi-use. For example, ecosystem services identified in the wind records have a greater emphasis on seaweed products, such as food, fertilizer, or feedstock for biofuel, rather than the regulating/habitat services or cultural services provided to coastal people. In fact, only two cultural services were identified in the wind records: sources of employment/income and improved quality of life. This underrepresentation of cultural services may be due to insufficient research on the cultural benefits of offshore multi-use or the fact that most studies of the cultural benefits of seaweed farming are focused on small-scale, community-based farms in poor, rural developing countries (Rimmer et al., 2021). The low capital and operational costs of conventional seaweed farming, in conjunction with a short production cycle and moderate labor, contribute to the livelihoods of local farmers; however, the expansion of seaweed production to offshore facilities would increase production to an industrial scale, potentially altering the socioeconomic benefits of seaweed farming (Rimmer et al., 2021).

The identified provisioning services of seaweed farming were consistent across all records and the offshore wind-focused records, with food products and agriculture products cited the most. This finding suggests that, regardless of where the seaweed is cultivated, confidence in the value of seaweed derived food and agricultural products remains strong. This is in alignment with the considerable amount of existing literature highlighting the nutritional value of seaweed, the use of seaweed extracts to enhance the growth of agricultural produce, and feed additives for cattle and horses (MacArtain, et al., 2007; Pereira, Bahcevandziev, & Joshi, 2020). Similarly, the regulating and habitat services were alike across all records and the offshore wind-focused records, but it is interesting to note that the wind records had a pattern of greater consideration for the potential of seaweed farms to mitigate climate change. Previous research has shown the potential for seaweed farming to contribute to climate change mitigation through carbon sequestration, but only under drastic upscaling scenarios (Duarte et al., 2017). The cultivation of seaweed within offshore wind farms would inherently increase the scale of production and total seaweed biomass, providing greater opportunities for farmed seaweeds to contribute to global climate change mitigation.

To realize the benefits of seaweed farm-offshore wind co-location, it is essential to address the challenges associated with this activity. It appears that environmental impacts are a major concern of seaweed farming, but particularly so for offshore wind multi-use sites. Both the constraints and knowledge gaps cited by all records identified the lack of a regulatory biosecurity framework as a primary concern for seaweed farming. The presence of nuisance species, such as pests or disease agents, can impact seaweed health and farming equipment via direct competition for resources, physical damage, or interference with farming infrastructure (Bannister et al., 2019), or can be released from a farm into the local environment (UNEP, 2023). Ultimately, nuisance species lead to a loss of seaweed biomass, reduced quality and commercial value of seaweed products, economic harm to farming operations, and ecosystem degradation (Bannister et al., 2019; UNEP, 2023). Strategic farming practices and an adequate biosecurity framework have been cited as essential for the future success of commercial seaweed farming operations (Cottier-Cook et al., 2016; Cottier-Cook et al., 2021).

Impacts to local marine ecosystems, constraints of physical/chemical oceanic conditions, and poor water quality were most cited for the co-location of seaweed farming with offshore wind. Competition of farmed seaweed with local marine algae, like phytoplankton, for light and nutrients is a considerable concern for offshore cultivation, especially for large-scale production that extracts a disproportionate amount of nutrients from the water column (Campbell et al., 2019). Additionally, shading, absorption of kinetic energy, and the addition of particulate matter can negatively impact benthic communities like seagrass beds (Campbell et al., 2019). Cultivation of seaweed offshore has high potential to deplete the availability of nutrients, and therefore, appropriate site selection is necessary to avoid impacting local marine ecosystems (Hancke et al., 2021). Subsequently, the physical/chemical oceanic conditions, such as strong wave currents, severe weather patterns, or inadequate nutrient availability of offshore waters pose a threat to successful farmed seaweed growth. Our exploration of cultivable species in New Jersey demonstrated that low nutrient availability in offshore waters is a clear constraint for seaweed cultivation. Addressing knowledge gaps relating to the environmental impacts of seaweed farming, and specifically competition for resources, is an area of future research need.

Summary/Conclusions

Seaweed farm-offshore wind multi-use holds the potential to provide provisioning resources and advance New Jersey's blue economy, yet the path forward yields many obstacles in the form of adequate site and species selection, potential environmental impacts, and a lack of a regulatory framework. Our study focused on two native seaweed species in New Jersey and a single offshore proposed lease location. Other native species may be suitable for offshore cultivation at other locations, and additional research into native New Jersey seaweed species is needed to expand this work. Moreover, the QSR was limited in geographical coverage, with most studies on seaweed farm-offshore wind multi-use focused within Europe, while Asian countries are the primary contributors to farmed seaweed biomass. This indicates a disconnect between seaweed farming activity and technological advancement, and therefore a potential barrier to the implementation of novel approaches. Moreover, relatively few studies in general have approached the topic of seaweed farm-offshore wind multi-use, indicating the early stage of inquiry into this topic. Our review nonetheless indicates that priorities for future research should include continued research on nutrient limitations to farms, the impacts of seaweed farming on marine ecosystems, and the legal governance of multi-use sites. Regarding the latter, next steps may include examinations into regional stakeholder views and values regarding the opportunities, constraints, and knowledge gaps of seaweed farm-offshore wind co-location, including in New Jersey.

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APPENDIX

Table A1. Summary of all data categories and subcategories extracted in the QSR.

Category+A1:C32A1:C50	Subcategories	Explanation
Year	-	Date of publication
Location	-	Country, countries, or geographic region study took place
Scale	N/A	Not specified
	Local	Cities, villages, specific farm sites
	National	Across whole country
	Regional	Multiple countries of a specific region
	Continental	Whole Continent
	Global	International, multiple countries across the globe (not just one region)
Study Type	N/A	
	BACI	
	Before-After	Studies considering conditions before seaweed aquaculture site is installed
	Control-Impact	Studies comparing natural communities and seaweed crops
	Descriptive	Studies based on observations, literature review, or descriptions of aquaculture
	Modelling	Studies using models to assess or identify ecosystem services
	Multidisciplinary	
	Other	
Species	-	Species or taxonomic group focused on. (Can be general)
Aquaculture Type	N/A	
	General	Not specified; seaweed aquaculture in a general sense
	Land-Based	Cultivation on land
	Transitional	Cultivation in estuarine or brackish waters
	Nearshore	Cultivation in marine waters <50m depth or <3nm distance to shore.
	Offshore	>3nm from shore
Farm Size	N/A	Not specified
	Experimental	Pilot or experimental plot
	Small	Family run, small villages
	Medium	(<50 lines per 200 m)
	Large	Cover whole bays, regions, or large coastal areas (>50 lines per 200 m)
Ecosystem Services	Provisioning	See **Table A2**
	Regulating and Habitat	
	Cultural	
Constraints	See **Table A3**	
Knowledge Gaps	See **Table A4**	
Negative Impacts/Trade offs	N/A	
	Aesthetic	
	Cultural heritage/activities	
	Diversification of Livelihoods	
	Ecotourism/recreation	
	Enhance fisheries by reducing pressures	
	Global Food Security	
	Improve quality of life for coastal communities	
	Local economic growth	
	Poverty Alleviation	
	Source of income/employment	
	Women Empowerment	
Multi-Use	N/A	No mention of seaweed aquaculture multi-use
	Wind Energy	Seaweed aquaculture combined with offshore wind farms
	IMTA	Seaweed aquaculture in Integrated Multi Trophic Aquaculture systems
	Other	

Table A2. Summary of all the Ecosystem Services data extracted in the QSR.

Ecosystem Services	
Subcategory	**Type**
Provisioning	Human consumption
	Agriculture
	Chemical materials
	Bioplastics/textiles
	Cosmetic/personal care products
	Medicinal, pharmaceutical, nutraceutical products
	Biofuel/Energy
	Other
Regulating and Habitat	Coastal protection
	Displacing more carbon intensive products
	Ocean carbon sequestration
Cultural	Source of income/employment
	Improve quality of life for coastal communities
	Women Empowerment
	Diversification of Livelihoods
	Poverty Alleviation
	Local economic growth
	Cultural heritage/activities
	Ecotourism/recreation
	Global Food Security
	Enhance fisheries by reducing pressures
	Aesthetic

Table A3. Summary of all Constraints subcategories extracted in the QSR.

Constraints	
Subcategory	**Type**
Political	Support
	Dependence
Environmental	Nuisance Species (pests, diseases, epiphytes)
	Weather
	Biological Shift
	Effects of climate change
	Predator/grazers
	Water Quality
	Appropriate site/species selection
	Genetic (crop to wild)
	Introduced Species (nonnative and invasive)
	Seasonality
	Pollution from Farming Equipment
	Emissions/Absorptions
	Visual/Noise Pollution
Social	Public Opinion/Support
	Occupational Health Hazarrds
	Stakeholder Conflicts
	Gender Inequalities
	Visual Impact
	Job
Technical	Technology
	Nursery
	Harvest
	Training
	Post-harvest
	Appropriate site/species selection
	Production
	Hazards
	Combat Climate Change
Economic	Costs
	Market (Value/Viability)
	Market (Volatile)
	Not sustainable income
	Market (Undeveloped)
	Financial Feasibility
	Other
Legal	Governance
	Biosecurity
	Food Safety
	Licensing/Permitting
	Spatial Planning

Table A4. Summary of all Knowledge Gaps subcategories extracted in the QSR.

Knowledge Gaps	
Subcategory	**Type**
Political	Support
	Dependence
Environmental	Wider ecosystem effects
	Appropriate species/site selection
	Nuisance species
	Water Quality
	Genetic (crop to wild)
	Emission/ Absorption
	Introduced Species
	Seasonality
	Effects of climate change
	Substrate (artificial habitat)
	Environmental Benefits
	Environmental- Carrying Capacity
	Weather
	Aquaculture type
Social	Gender Inequalities
	Jobs
	Lack of Data
	Occupational Health
	Public Opinion
	Cultural/Historical Significance
	Social (general)
	Stakeholder
Technical	Nursery
	Production
	Post-Harvest
	Technology
	Species Selection
	Product Quality
	Harvest
Economic	Costs
	Market value/viability
	Life Cycle Assessment
	Financial Feasibility
	Economic and Technical Integration
Legal	Governance
	Biosecurity
	Food Safety
	Legal (general)