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Ecosystem Services Provided by Seaweed Cultivation: State of the Art, Knowledge Gaps, Constraints and Future Needs for Achieving Maximum Potential in Europe

Fricke A[a], Capuzzo E[b], Bermejo R[c], Hofmann LC[d,e], Hernández I[f], Pereira R[g], Van den Burg SWK[h], Pereira T[i], Buschmann AH[j] and Cottier-Cook EJ[k]

[a]Department of Quality, Leibniz Institute of Vegetable and Ornamental Crops (IGZ), Großbeeren, Germany; [b]Centre for Environment, Fisheries and Aquaculture Science (Cefas), Weymouth, UK; [c]Instituto Andaluz de Biotecnología y Desarrollo Azul (IBYDA), Department of Ecology and Geology, University Campus of Teatinos, Malaga, Spain; [d]Helmholtz Center for Polar and Marine Research, Alfred Wegener Institute Helmholtz Center for Polar and Marine Research, Germany; [e]Bremerhaven University of Applied Sciences, Bremerhaven, Germany; [f]Department of Biology, University of Cadiz, Puerto Real, Spain; [g]Algae for Future, A4F, Lisbon, Portugal; [h]Wageningen Economic Research, Wageningen University & Research, The Hague, Netherlands; [i]Interdisciplinary Centre of Marine and Environmental Research (CIIMAR), University of Porto, Matosinhos, Portugal; [j]Centro i-mar, MASH & CeBiB, Universidad de Los Lagos, Puerto Montt, Chile; [k]Scottish Association for Marine Science, Oban, UK

ABSTRACT

The potential of seaweed as a renewable resource is becoming increasingly recognized by diverse stakeholders in Europe. Currently, several initiatives are working on accelerating the development of the European algae industry. Seaweed cultivation can be an important cornerstone in developing EU aquaculture and achieving the European Green Deal. An expert working group was selected and established in February 2021 by the European knowledge brokering mechanism Eklipse. This group was tasked to explore and map the current state of knowledge regarding ecosystem services (ES) provided by seaweed cultivation, including knowledge gaps, constraints, potential negative impacts and tradeoffs. The study was based on the Delphi process and a Quick Scoping Review (QSR). The results of each method showed differences in constraints, negative impacts and knowledge gaps, revealing the need for better communication and collaboration between the involved stakeholders. Both methods identified the following six ES provided by seaweed cultivation: (i) provisioning food, (ii) provisioning hydrocolloids and feed, (iii) regulating water quality, (iv) provisioning habitats, (v) provisioning of nurseries and (vi) regulating climate. Nevertheless, the specific ES identified differed between seaweed taxa. In addition, both methods highlighted also potential negative environmental impacts (e.g., wider ecosystem effects), technological constraints and knowledge gaps (e.g., production). The identified knowledge gaps and constraints were further discussed and prioritized with stakeholders in a workshop in Brussels. This workshop identified the structural research needs for future investigations, including: improved knowledge of environmental impacts; better management of genetic diversity and clear definitions of legal frameworks to support the development of the EU initiative on seaweed sustainable use. This paper summarizes the findings of the investigations of the expert group and future challenges for seaweed cultivation under current and near-future climatic scenarios.

KEYWORDS

Seaweed cultivation; macroalgae aquaculture; ecosystem services; knowledge gaps; Europe; aquaculture strategy

Introduction

The human population is predicted to reach 9.7 billion by 2050, increasing the demand for food, clean energy, water and land (Lal 2016). This demand is driving the need to find innovative ways to produce food and other products, which do not impact the wider environment or encroach on existing farming systems. As the capacity of terrestrial agriculture to meet future food demands is being increasingly challenged by limited arable soil, soil degradation, droughts, flooding and salinization of aquifers, among others (Laurance et al. 2014; Crist et al. 2017), attention from the general society is increasingly shifting to the oceans. Activities based on low trophic level organisms, such as the cultivation of macroalgae (seaweeds), which require minimum freshwater or additional nutrient inputs, have therefore received increasing attention globally over the last decade (Cai et al. 2021).

CONTACT Fricke A fricke@igzev.de Department of Quality, Leibniz Institute of Vegetable and Ornamental Crops (IGZ), Großbeeren, Brandenburg, Germany.
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Seaweed farming, second only to finfish cultivation in terms of production volume, yields over 35 MT annually (FAO 2022). In countries such as China, Indonesia or the Philippines, seaweeds have been cultivated in farms on a commercial scale for over 50 years, covering several thousand kilometers of the ocean (Cai et al. 2021). Seaweeds have been a staple dietary component in many Southeast Asian countries for millennia. Seaweeds provide important ingredients for humans (Blikra et al. 2021) and animal feeds (Morais et al. 2020), where they potentially mitigate methane release by improving the productivity of ruminant livestock (Kinley et al. 2020; Lean et al. 2021). They also serve as ingredient in formulated diets for fish (Wan et al. 2019) and even provide an added- functional value by decreasing the use of antibiotics in aqua- and agriculture (Thanigaivel et al. 2023). The potential value of seaweed cultivation as a nature-based solution (NBS) to both address the growing global issue of food insecurity (Radulovich et al. 2015; Jagtap and Meena 2022) and to provide ecosystem services, such as CO_2 sequestration, eutrophication mitigation, pollution mitigation, coastal protection, local biodiversity and water quality improvements (Duarte et al. 2017; Jiang et al. 2020; Hynes et al. 2021, Hasselström et al. 2018) is being increasingly scrutinized. In countries, such as the USA, Norway and Namibia the public and private sectors are now investing heavily in cultivation technologies, which could enable the production of thousands of tonnes of seaweed biomass (FAO 2020, UN 2024). Nevertheless, it remains to be seen if such production numbers will be realized

Seaweed cultivation in Europe is considered to be relatively new, with the first small-scale farms being established in early 1985 (Barbier et al. 2020). With increasing demand for seaweeds globally, farming techniques pioneered in China and Southeast Asia have been successfully employed in Europe, particularly Norway, Scotland, Ireland and France. The large, brown kelps *Saccharina latissima* and *Alaria esculenta* are the main seaweed species currently cultivated in Europe, with farms ranging in size from <5 - 100 ha, producing 1450-2100 t annually (Barbier et al. 2020; FAO 2022). At present, European legislation and policies typically govern the industry (Barbier et al. 2020). For example, The Water Framework Directive 2000/60/EC and the Council Regulation EC No. 708/2007 of June 2007 concerning the use of alien and locally absent species in aquaculture, cover aspects of cultivation, including sourcing seed from sustainable stocks, biosecurity control measures to minimize the spread of pests and diseases, a ban on fertilizers, maintenance of infrastructure and site selection of farms to minimize disturbance to protected environments (Campbell et al. 2019). The European Commission is currently implementing an EU Algae Strategy, which needs to take into consideration the multiple areas where seaweed cultivation can contribute to the European Green Deal and the development of a sustainable European Blue Bio-economy (Commission E 2022). The successful implementation of this strategy requires that the knowledge gaps, constraints, and potential negative impacts related to seaweed cultivation are identified and research is funded to address them to enable the sustainable growth of this industry.

To inform future developments of seaweed culture strategies and policies in Europe, an expert working group (EWG) was selected and established in February 2021 by the knowledge brokering mechanism Eklipse (Eklipse Contract CfR.5/2020/1) under the request of DG Maritime Affairs & Fisheries, Unit for Maritime Innovation, Marine Knowledge and Investment. The EWG comprised of experts from across Europe and Chile, from academic and industry sectors were tasked to explore and map existing knowledge gaps, constraints, potential negative impacts and tradeoffs related to seaweed cultivation. In particular, the state of knowledge and any related knowledge gaps regarding the potential of seaweed culture in providing climate-related and other ecosystem services was investigated and reported on to the European DG for Maritime Affairs and Fisheries (Bermejo et al. 2022). The present study captures the findings of this investigation and the outcome of the subsequent stakeholder workshop, which was carried out in June 2022, to discuss further challenges of the envisaged upscaling of the seaweed industry across Europe. Moreover, it captures additional data (e.g., FAO Fisheries and Aquaculture Statistical Query Panel for aquaculture quantities), more recent studies and further discusses the findings to provide a more complete overview of the potential of seaweed aquaculture in Europe.

Material and methods

Two methods were used in parallel to determine the state of knowledge and the gaps in this knowledge related to the provisioning of ecosystem services by seaweed cultivation; (i) a Quick Scoping Review (QSR) and (ii) a multiple expert consultation using the Delphi process.

The QSR was used for a systematic and objective study of evidence from scientific literature. To reduce the time and expense of implementation, this method did not include a critical appraisal of the evidence. The lack of a critical appraisal limits the use of this methodology to directly inform a decision, but provides a general understanding of the evidence base, which is useful to inform general policy direction (Collins et al. 2015). The Delphi process is an iterative technique for collecting information using expert consultation in a structured manner, suitable for evaluating complex problems (Dalkey and Helmer 1963); Mukherjee et al. 2015). In this study, the process capitalized on expert knowledge to identify and prioritize the relevant ecosystem services and identify constraints for up-scaling, tradeoffs and negative impacts of seaweed farming.

Quick scoping review (QSR)

To investigate the current scientific knowledge of ecosystem services provided by seaweed cultivation, a quick scoping review (QSR) was performed, considering peer-reviewed original research articles (thus excluding reviews, conference papers, letters, books and book chapters), written in English. Documents were treated in three different steps; (i) identification, (ii) screening and (iii) eligibility. A search was conducted in two databases, Scopus and Web of Science (WoS) on 16th June 2021, using combinations of primary terms "macroalga" and "seaweed", and the secondary terms "cult*", "farm*" and "aquaculture", and wildcards within the "Title, Abstract and Keywords". The keywords were limited to the abstract and title. Data was compiled in Mendeley (reference management software) and duplicates were removed using the software, resulting in a total of 1229 entries. The search included literature published between January 2000 and June 2021 (the date of the review search), as the ecosystem service concept was developed in the early 2000s and defined in the framework of the Millenium Ecosystem Assessment (World Resource Institute 2005). The resulting entries were sorted in an Excel spreadsheet and the articles were sorted and screened according to formal inclusion criteria (Table 1 - Phase 1). A total of 960 articles were identified to be further assessed based on title, abstract and defined criteria (Table 1 - Phase 2) to determine whether the articles should be part of the review. This screening resulted in a total of 280 articles, which provided the basis of the analytical part of the QSR and are listed in Supplemental Table 1. To avoid potential bias by individual decisions, the eligibility of each article was assessed by two experts. In case of disagreement, a third expert assessment was conducted.

Table 1. Overview of inclusion criteria applied in phases 1 (formal criteria) and 2 (title and abstract review) of the Quick Scoping Review (QSR).

Phase 1: formal criteria	
Language:	english
Date of publication:	between 01/2000 and 06/2021
Type of work considered:	peer-reviewed original research articles
Database:	available in SCOPUS or Web of Knowledge (WoK)
Phase 2: Title and Abstract / Phase 3: Full text	
Research base:	seaweed aquaculture systems (> 100 L tanks)
Research foci:	assessment of services, risks and disservices connected with seaweed aquaculture; spatial and temporal assessment of seaweed aquaculture; studies on the biotic interplay related to seaweed aquaculture

Delphi process

Over 130 experts from 40 countries, including 15 EU countries, were identified to participate in a maximum of three planned rounds of questioning. The geographic distribution of experts was global, but considering the focus on seaweed cultivation in Europe, approximately 70% of them were from Europe and 30% from elsewhere. An approximate ratio of 3:3:2:2 representation from academia, industry, NGOs, and other marine organizations, respectively, was adopted. Consequently, 104 experts were invited to participate. The invitees were sent the work document prepared for the query. In addition to a general introduction and the actual questions for the first round, it also included a set of background questions. These sections were created to facilitate the interpretation of the results and, if needed, to allow the implementation of selection criteria, which could be considered necessary to comply with the agreed balance between regions and activity sectors. Out of the 104 experts contacted during the first round, 22 participants responded. From these respondents over 40% were from Europe. The remaining responses were from participants from Asia and the Pacific, Latin America and the Caribbean and North America (~14% each), the Near East (7%) and Africa (~3.5%). The majority (68%) of respondents were from the academic sector and 18% from industry, followed by professional and international organizations (5% each) and NGOs (5%). The respondents had experience in macroalgae cultivation (37.5%), macroalgae hatcheries/nurseries (27.5%), macroalgae processing (17.5%) marketing and sales (5%), macroalgae genetic characterization and breeding (2.5%), education (2.5%), management and conservation of brown algae (2.5%), and kelp forest studies, seaweed diversity and phylogeography (2.5%). The responses were analyzed and consolidated into a revised questionnaire for the second round, providing a list of ecosystem services, knowledge gaps and negative impacts or tradeoffs identified in the first round. The respondents were asked to rank these in order of importance or severity. Only six experts responded to this round, therefore, due to the low response rate, it was decided to not proceed with a further third round of questions. Due to the low number of responses, the results of this Delphi process cannot be considered representative. Nevertheless, these data are presented with the caution that must be exercised.

Combined analysis of QSR and Delphi

The use of the two methods in parallel helped to provide a more comprehensive overview than the use of a single method alone. While the QSR focused on peer-reviewed literature, the Delphi process captured the most recent and up-to-date views of experts from key sectors, including science, business, NGOs, and other societal actors with practical and experience-based knowledge on key issues in seaweed cultivation. Moreover, the combined methods helped to identify existing knowledge gaps, since the lack of literature in targeted areas of interest became evident in the results from the QSR, and the Delphi process went even further, by asking experts to formulate pathways for filling the identified knowledge gaps.

To analyze the outcome of both methods, a PESTLE approach was adopted (Basu 2004), classifying the papers and expert responses according to six external key factors; (i) Political, (ii) Economic, (iii) Social, (iv) Technological, (v) Legal and (vi) Environmental. Ecosystem services (ES) were categorized based on the Common International Classification of Ecosystem Services (CICES 5.1) (Haines-Young and Potschin-Young 2018). In addition, the identified ES for seaweed aquaculture were compared to the United Nations Sustainable Development Goals (SDGs; UN General Assembly, 2015). To provide a general insight into the volume and characteristics of the evidence found in the scientific literature, a template was designed to extract relevant information. The recorded information included: (1) species, (2) country, (3) scale, (4) sector, (5) PESTLE classification, (6) aquaculture type (land-based, near-shore -within 3 km from shore- and offshore – > 3 km from the coast; Bak et al. 2020), (7) study protocol, (8) farm size, (9) contribution to different ecosystem services (ES) grouped under 3 main categories: provisioning, regulating and maintenance or cultural), (10) knowledge gaps, (11) identified constraints (which limit or influence the productivity of the seaweed farms), (12) disservices/negative impacts (that cause direct negative effects on seaweed cultivation), (13) disservices comments and (14) expert notes were also provided. To identify the main drivers and causes within the different PESTLE categories for seaweed cultivation, the relative percentages of constraints, negative impacts and knowledge gaps revealed from the QSR were summed and ranked (cumulative interest, CUM INT).

Seaweed production – biomass vs. publication

To provide an overview of the global seaweed production and compare it to the outcome of the QSR, estimates of global aquaculture production were obtained for the year 2020 through the FAO Fisheries and Aquaculture Statistical Query Panel for aquaculture quantities (https://www.fao.org/fishery/statistics-query/en/aquaculture/aquaculture_quantity). The dataset was queried to obtain production of 'Aquatic Plants' for all countries listed, in both brackish waters and marine waters.

Workshop evaluation

Based on the final Eklipse evidence report launched in May 2022 (Bermejo et al. 2022), a workshop on the science-policy interface regarding seaweeds, their ecosystem services and impacts, was co-convened by DG-MARE and Eklipse and logistically organized by MCI-Brussels. The professionally facilitated workshop took place in Brussels on the 13th of June 2022 (Eklipse 2022), and aimed to (a) further identify and prioritize knowledge gaps regarding seaweed cultivation and ES; (b) identify structural research needs, which can feed into future research initiatives of the European Commission and (c) further support the development of the EU Algae Initiative. During this workshop, a mixed stakeholder group of 31 persons, including members of the EWG, representatives of Eklipse, the requester DG Mare (also representing the EU Algae Initiative) and experts from diverse scientific organizations, identified and discussed four different key topics related to the upscaling of seaweed cultivation in Europe. In particular, Topic 1: Better understanding of biological and ecological components; Topic 2: Better understanding of farming production systems for Europe; Topic 3: Better understanding of environmental impacts and Topic 4: Better understanding of value chains, market acceptance and economic scenarios. Each topic was moderated by a member of the Eklipse EWG and the topics were addressed in a Samoan circle, a leaderless variation of the fishbowl discussion approach. This

Samoan circle approach helps to overcome anxiety when discussing issues with multiple points of view. It has people seated in concentric circles, where only those in the inner circle are allowed to speak. Participants in the outer circles can move to the inner circle at any time to contribute. Participants chose two questions to address in the inner circle. The first topic was identifying the current knowledge gaps, which was discussed for about 30 min. For the second topic participants reflected on the identified knowledge gaps, which lasted 20 min.

After the Samoan circle group discussion, participants were divided into 4 breakout groups, with one facilitator and one expert assigned to each, addressing 4 topics previously identified; (i) Biological and ecological components, (ii) Farming production systems for Europe, (iii) Environmental impacts, and (iv) Value chains, market acceptance, and economic scenarios. The group discussions were done in two rounds. In the first round, participants were asked to write down the most important knowledge gaps related to the topic of their group. In the second round, participants moved to another group and elaborated further on the knowledge gaps identified in the first round. As a final step, all participants were requested to prioritize the listed knowledge gaps according to three criteria: (i) policy relevance, (ii) innovation and (iii) feasibility. For this final task, each criterion was assigned a color, and three colored dots of each color were distributed by the participants. These were then used as a voting system to identify the most relevant of the key knowledge gaps identified according to their perception. Final rated worksheets, including a list of knowledge gaps and associated colored dots were photographed and analyzed. Within each topic, corresponding knowledge gaps were grouped and rated according to the number of dots received (i.e., their summed importance).

Results

Global interest in seaweed cultivation and production

Analyses of the number of publications on seaweed cultivation between 2000 and 2020, showed an increasing scientific interest in the topic, with over 45 eligible articles published in 2020 alone (Figure 1A). Interestingly, comparing the scientific output to the regional seaweed production for each geographical area highlighted substantial discrepancies between the volume of scientific publications and production. Asia, the global leading seaweed producer (> 34 million tons of fresh weight in 2020) had a publication output accounting for 30% of relevant papers identified through the QSR. Contrarily, Europe only accounted for < 1% of global production, yet produced 24% of the in English written, peer-reviewed publications investigated in the QSR (Figure 1B).

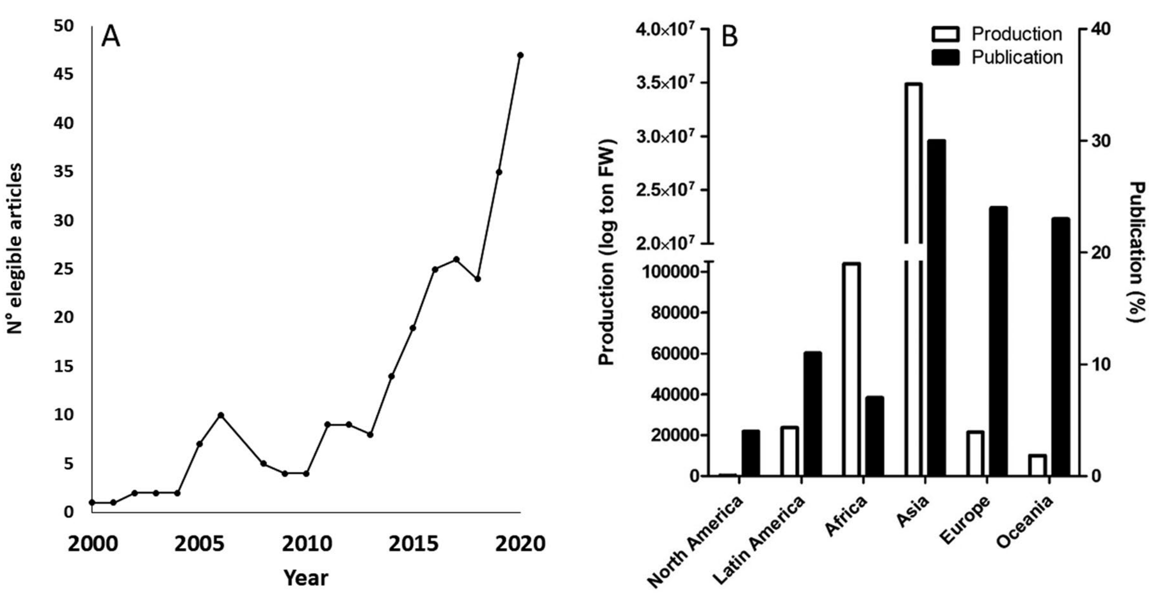

Figure 1. Global interest in macroalgal cultivation and production A) Rising number of eligible articles, identified by QSR and sorted by year of publication for the period 2000 to 2020. B) Comparison of percentage publication contribution based on eligible articles published between 2000 and June 2021 and macroalgal production data of the year 2020 based on FAO Global aquaculture production database, by geographical area.

Regional seaweed cultivation

Strong regional differences were identified based on the taxonomic identity of the cultivated seaweed. Kelps (order Laminariales) were globally the most dominant group studied, followed by the red algae Eucheumatoids and Gracilarioids (Figure 2). In North America and Europe, the studies were dominated by research on kelps, whereas in Africa and Oceania studies were more focused on Euchematoids. In Latin America and Asia, the studies appeared more evenly distributed between the different groups, although there was a slight increase in focus on Gracilarioids. Studies on Ulvales (as well as Gracilarioids) were found globally. The research interest in *Porphyra/Pyropia* seemed to be particularly focused on Asia. Overall, a total of 37 macroalgae genera comprising 77 species was identified in the QSR, including 17 species in studies focused on Europe. The four most studied seaweeds belonged to the kelps, with sugar kelp *Saccharina latissima* as the most dominant species (59% of all seaweed cultivation-related studies in Europe) (Table 2).

Seaweed farming types

The majority of the studies were conducted in near-shore farms (60%), followed by land-based (12%) and offshore farms (6%) (Table 3). Among near-shore farms, it was not possible to discriminate between types of water (e.g., seawater, brackish or transitional water). Many publications did not specify the size of the seaweed farm. Where size farm details were provided, most seaweed cultivation was done for near-shore and land-based farms on a pilot or small scale, while studies on off-shore aquaculture comprised mainly medium to large scale.

Overview of ecosystem services identified

From the QSR and Delphi approaches, 15 sub-categories were identified from the three main categories of ecosystem services (ES) provided by seaweed farming: (i) *regulating and maintenance* (water quality, biological regulation, climate regulation, coastal protection, other uses), (ii) *provisioning* (biomass, hydrocolloids (food), food, feed, energy (biofuel)), (iii) *cultural* (education, tourism, social welfare, scientific knowledge, symbolic). Clear differences were visible between the QSR and Delphi approach in the evaluation of ES. While regulating and maintenance services, as provisioning services, were nearly equally ranked in the literature, regulating and maintenance services were given higher importance in the Delphi questionnaires (Table 4). In both approaches, water quality was identified as the main subcategory for regulation and maintenance. For provisioning, food production played a leading role in the QSR, but was less differentiated in the Delphi. As cultural services, education was identified as the main sub-category in both approaches and was the only one considered in the Delphi.

The sub-categories of ES were then considered within the context of the UN SDGs (UN General

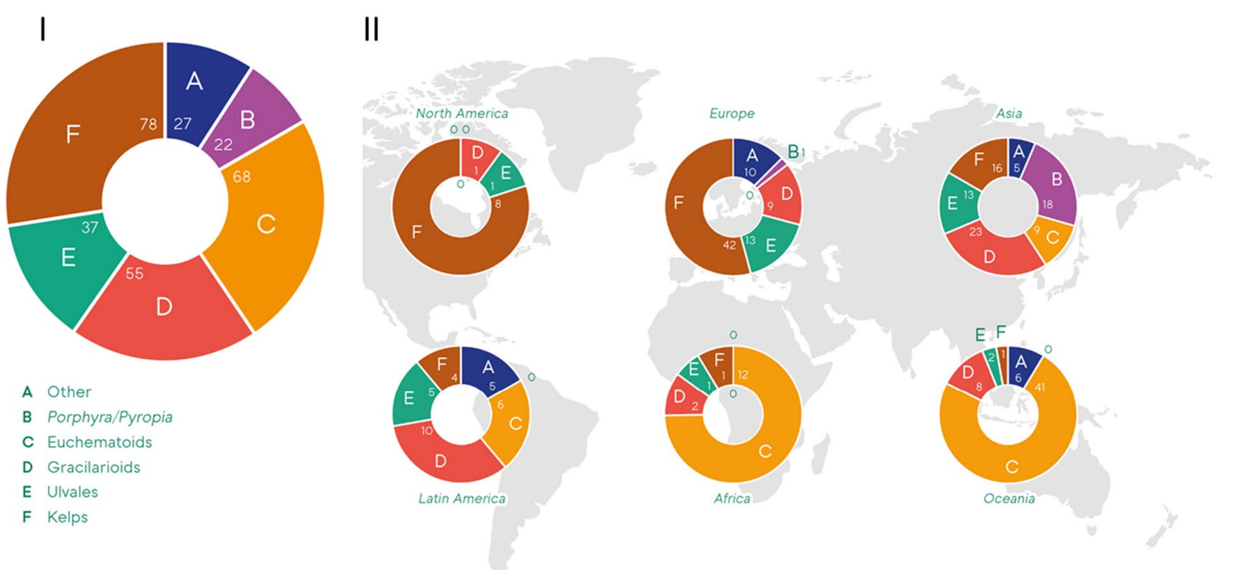

Figure 2. Differences in regional macroalgal cultivation. (I) Overall contribution of macroalgal groups to global seaweed cultivation and (II) regional differences on cultivated taxa. Data based on QSR. Figure taken from Bermejo et al. 2022).

Table 2. Seaweeds cultivated in Europe for commercial or research purposes identified in the QSR.

Type	Name	Studies (%)
Kelps	Saccharina latissima (sugar kelp)	59
Kelps	Laminaria digitata	14
Kelps	Alaria esculenta	11
Kelps	Undaria pinnatifida	5
Ulvales	Ulva rotunda	5
Ulvales	U. intestinalis	4
Ulvales	U. rigida	4
Ulvales	U. lactuca	2
Gracillariods	Gracilariopsis longissima	5
Gracillariods	G. gracilis	4
Gracillariods	G. vermicullophylla	2
Gracillariods	G. bursa-pastoris	2
Other	Palmaria palmata.	*4*
Other	Chondracanthus teedei	4
Other	Asparagopsis armata	4
Other	A. taxiformis	2
Other	Furcellaria lumbricalis	2

Table 3. Overview of information on seaweed farming types and sizes, identified on QSR. Table provides information of three distinguished farm types: land based, near-shore (within 3 nm from shore) and offshore, in relation to total studies analyzed ($n = 280$) and the relative differences in their sizes (%-contrib.).

Type (% of total)	Size	%-Contr.
Near-shore (60%)	pilot to small	47
	medium to large	35
	no info	18
Land-based (12%)	pilot to small	64
	medium to large	9
	no info	27
Off-shore (6%)	pilot to small	25
	medium to large	44
	no info	31

Assembly, 2015). Seaweed cultivation addresses many of the SDGs (Figure 3), particularly goals 14 (life below water), 11 (sustainable cities and communities) and 12 (responsible production and consumption). Seaweed cultivation contributes to the target to prevent and significantly reduce marine pollution (e.g., from land-based activities) and to increase scientific knowledge, develop research capacity and transfer marine technology within SDG 14. As bioremediation of marine waters can contribute to sustainable management of water resources and supplying access to safe water, the bioremediation services provided by seaweeds also closely link to SDG 6. Seaweed cultivation also addresses the protection of cultural and natural heritage *via* sustainable tourism (SDG 11), zero hunger (SGD2), good health and well-being (SDG 3), affordable and clean energy (SDG 7), reduced inequalities (SDG 10), and climate action (SDG 13). The collaboration and efforts to develop this publication and associated report, including sharing knowledge and expertise, can also be considered a contribution to global partnerships and sustainable development, under SDG 17.

Table 4. Ecosystem Services (ES) provided by seaweed cultivation following the CICES classification based on the outcome of QSR and Delphi. The percentage of articles assigned into each ES category (Provisioning, Regulating & Maintenance and Cultural) during the QSR is provided as well as the percentage of those articles that contribute to each specific service (contr.%). The results of the Delphi Process show the percentage of ES provided by macroalgae cultivation in each category that were identified by the expert responses. as well as the percentage breakdown by specific services.

	QSR	Delphi
Regulating and Maintenance	**45%**	**86%**
Water quality*1	49 contr.%	36 contr.%
Biological regulation*2	30 contr.%	4 contr.%*3
Climate regulation*4	16 contr.%	27 contr.%
Coastal protection*5	1 contr.%	32 contr.%
Other uses	4 contr.%	
Provisioning	**48%**	**12%**
Biomass	36 contr.%	71 contr.%
Hydrocolloids (food)	30 contr.%	
Food	28 contr.%	
Feed	6 contr.%	
Energy (biofuel)		29 contr.%
Cultural	**6%**	**2%**
Education	65 contr.%	100 contr.%
Tourism	12 contr.%	
Social welfare	12 contr.%	
Scientific knowledge	6 contr.%	
Symbolic	6 contr.%	

*1(eutrophication, biomitigation, bioremediation).
*2(alien species, biodiversity/ genetic conservation, habitat provision, algal bloom regulation).
*3(habitat formation, pest control).
*4(CO2, carbon cycle, DMS).
*5(erosion, wave reduction).

Ecosystem services provided by different seaweed groups

Based on results from the QSR, each seaweed group provides multiple ES, but the heavily studied kelps were shown to provide the highest number of ES (Figure 4). 'Water quality' regulation represented the most commonly reported ES for Gracilarioids (49%), Ulvoids (48%) and kelps (41%). Whereas for Eucheumatoids, the provision of hydrocolloids (50%) was identified most often. For *Porphyra/Pyropia* biological regulation (43%) was identified as the most studied ES. In terms of provision of cultural ES, Eucheumatoids were identified to provide 'Education & learning', 'Scientific knowledge' and 'Social welfare' (23% of services provided), why for kelp only 4% of the total ES were made up by cultural services ('Education', 'Recreation & tourism'), and no cultural ES were reported for the other seaweed groups.

PESTLE categorization of constraints, negative impacts and knowledge gaps

Of all 280 studies investigated in the QSR, 35 studies (12%) exhibited weaknesses in their experimental design and were excluded from further analysis.

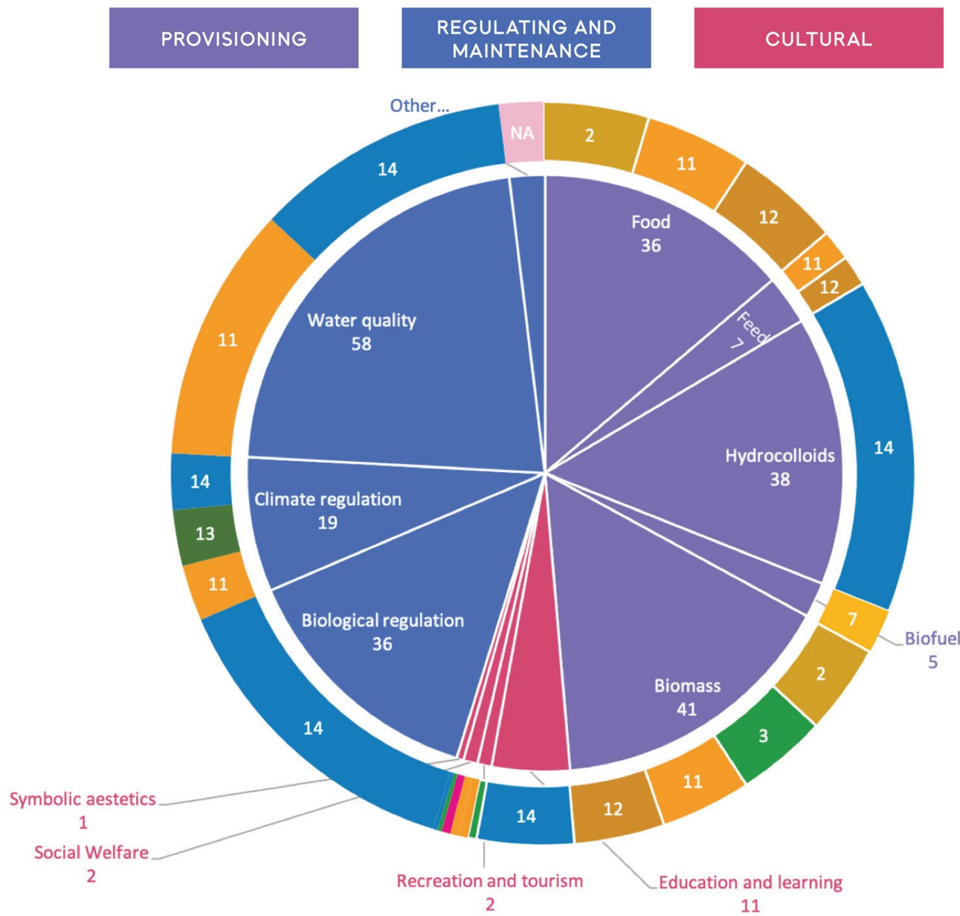

Figure 3. Ecosystem services (ES) and sustainable development goals (SDGs) provided by seaweed cultivation. Relationship between each type of ES provided by seaweed cultivation (inner pie chart) and the related UNSDGs (outer doughnut), based on the studies from the QSR. ES are color-coded according to the CICES classification (Provisioning, Regulating and Maintenance or Culture Services). The UN SDGs are 2- zero hunger, 3- good health and well-being, 4 - quality education, 7 - affordable and clean energy, 10-reduced inequalities, 11-sustainable cities, 12-responsible consumption and production, 13-climate action, 14-life below water. Figure taken from Bermejo et al. 2022.

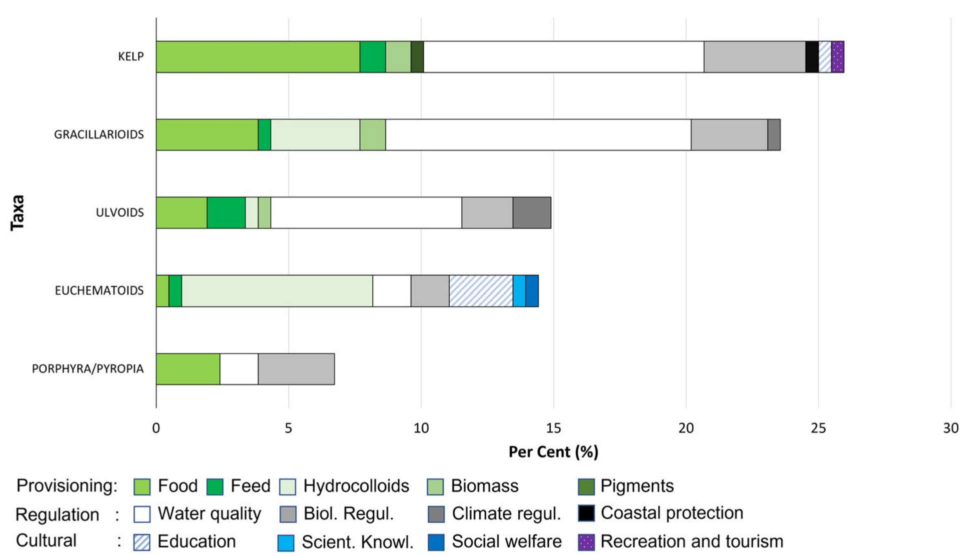

Figure 4. Percent contribution of Ecosystem services (ES) provided by algae groups, based on 208 publications reviewed. In the legend provisioning = food, feed, hydrocolloids, biomass, pigments; regulation = water quality, biological regulation, climate regulation, coastal regulation; cultural = education/learning, scientific knowledge, social welfare, recreation and tourism.

In addition, 1% of the remaining studies claimed the need for more environmental data to allow more concise studies and data sets (environmental constraints: data). These decisions were made based on the methods section of each article and on EWG experience, as authors and reviewers, rather than on authorship, species, geographical location or any other factor. Overall, six categories with subsequent sub-categories listed in Table 5 were identified, namely political (POL, 4 subcategories), economical (ECO, 3 subcategories), social (SOC, 7 subcategories), technical (TEC, 7 subcategories), legal (LEG, 2 subcategories), and environmental (ENV, 11 subcategories).

Identified constraints, negative impacts and knowledge gaps

Strong differences were observed between the PESTLE categories for constraints (factors limiting or influence the productivity of the seaweed farms), negative

Table 5. Overview of PESTLE (Political, Economic, Social, Technological, Legal and Environmental) and related sub-categories defined for seaweed cultivation.

PESTLE	Sub-category	Definition
Political (POL)		
POL-1	ABS	Access benefit sharing
POL-2	Dependance	Close relation / connection to other activities, e.g., wind parks
POL-3	Space	Use of space
POL-4	No Support	Need to develop policies to guide markets
Economical (ECO)		
ECO-1	Financiation	Financial viability, co-culture potential, sharing of ABS agreements
ECO-2	Market	Market and value chain elements
ECO-3	LCA	Life Cycle Assessment for different products (e.g. biofuel, protein, liquid fertilizers) and culture environments (e.g.seawalls). Need to consider climate change in risk analysis
Social (SOC)		
SOC-1	Gender	Gender inequality observed
SOC-2	Jobs	Jobs connected with seaweed aquaculture
SOC-3	Stakeholder	Stakeholder perception
SOC-4	Occupational Health/Working conditions	Safety of farmers
SOC-5	Coping with climate change	Adaptive strategies for seaweed farming communities to cope with climate change
SOC-6	Esthetical and Art	Esthetical and art applications of seaweed farming
SOC-7	Network	Stakeholder networking
Technical (TEC)		
TEC-1	Nursery	Seedling, stock quality, new strains in cultivation
TEC-2	Post-Harvest	Management and processes after harvesting
TEC-3	Harvest	Timing, techniques etc. harvest-related
TEC-4	Production	Amount of produced biomass, production speed
TEC-5	Product quality	Quality of seaweed products
TEC-6	Training	Training of people
TEC-7	Technology	Development in technology
Legal (LEG)		
LEG-1	Governance	Governance (e.g., co-location of seaweed farms with offshore wind), spatial planning, biosecurity
LEG-2	Contaminant limit	Concentration for certain contaminants (e.g. bacteria)
Environmental (ENV)		
ENV-1	Data	Insufficient amount of environmental data, uncertainty associated with modeling, need for more validated models, need for systematic data collection
ENV-2	Seasonality	Seasonal/ interannual effects, e.g., growing/harvesting period
ENV-3	Weather	Effects of storms and extreme events
ENV-4	Substrate	Effect of present natural or artificial substrate (type, conditions), creation of novel habitats
ENV-5	Emission/Absorption	CO2, balance of nutrients - footprint, species dependent, carbon footprint, impact of emission of volatile halocarbons
ENV-6	Nuisance species	Encrusting or epiphytic organisms affecting biomass quality or cultivation process, diseases, biofouling
ENV-7	Algal blooms	Related formation of algal blooms, HABs
ENV-8	Water conditions	Water quality and remediation processes and pollution load, nutrient inputs from terrestrial systems, sedimentation
ENV-9	Grazer	Grazing on cultivated macroalgae
ENV-10	Invasion and gene flow	Introduced species, population etc. spreading in comparison to local types, relationship between native and wild populations, maintenance and biosecurity, geographical distance and habitat discontinuity
ENV-11	Wider ecosystem effects/Biological shift	Effect of farms on coral reefs, phytoplankton communities, seagrass beds, fish assemblages/ landings, fish farms, potential overharvesting of wild stocks, microbial communities, impact of associated communities post-harvest, creation of novel habitats, effect of stocking density, persistence of ecosystem services when seaweed cultivated

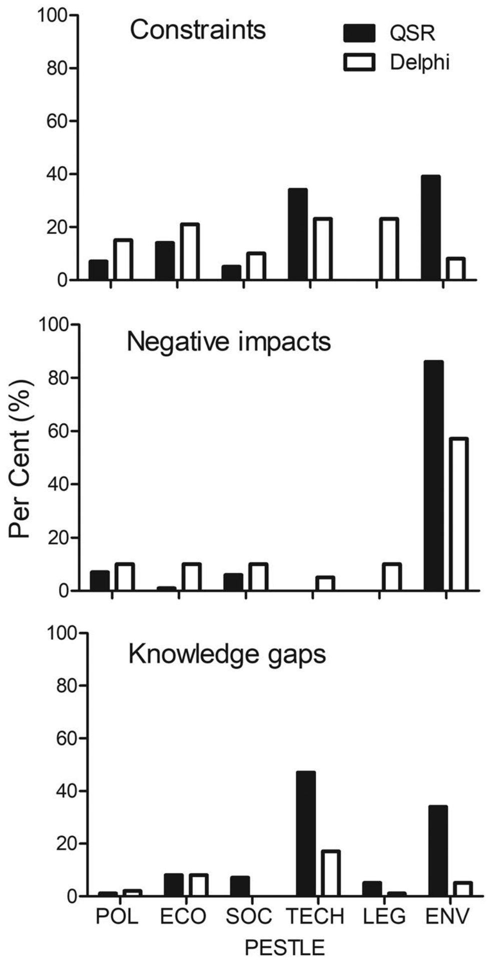

Figure 5. Percentage of constraints (factors limiting or influence the productivity of the seaweed farms), negative impacts (factors causing direct negative effects on seaweed cultivation) and identified knowledge gaps (lack of information or understanding) related to seaweed cultivation based on results from the QSR (black bars) and Delphi (white bars) assigned to different PESTLE (ENV = environmental, TECH = Technical, POL = Political, SOC = Social, LEG = Legal) categories.

impacts (factors causing direct negative effects on seaweed cultivation) and knowledge gaps (lack of information or understanding) identified by the QSR and the Delphi (Figure 5, Table 6).

a) constraints

Environmental constraints were most dominant (39%) according to the QSR, whereas they were considered less important based on the Delphi process (8%) (Figure 5A). In both approaches, nuisance species (QSR: 28%, Table 6; Delphi: e.g., "pest and pathogen infestation", Supplemental Table 3) were identified as an important sub-category. The technical category was considered important in both the QSR (34%) and the Delphi process (23%) (Figure 5A), with "production" identified as the top technical constraint (QSR: production 24%, product quality 10%, Table 6), including "adaption of innovations in culture systems" and "production in large scale – mechanization" (Delphi, Supplemental Table 2). Also, the improvement of seaweed nurseries (QSR: 16%, Table 6), by e.g., improving "seedling quality" and "exploration of wild stocks" (Delphi, Supplemental Table 2) was considered to play an important role. Despite the relatively high legal constraints (23%, Figure 5A) identified by experts in the Delphi process, none were identified in the QSR, reinforcing the lack of an "appropriate legal framework" identified by experts (Supplemental Table 2).

b) negative impacts

Six of the 22 expert responses (27%) identified none or only limited impacts caused by upscaling of seaweed aquaculture (Supplemental Table 3). Environmental impacts were considered the leading negative impacts in both approaches (QSR: 86%, Delphi: 57%, Figure 5B). Wider ecosystem effects (QSR: 31%, Table 6), algal blooms, (QSR: 29%, Table 6), and nuisance species (QSR: 27.6%, Table 6), including diseases and pests carrying organisms, such as parasites (Supplemental Table 3) were considered to cause the main environmental problems.

c) identified knowledge gaps

For the knowledge gaps, weaknesses were identified in the technical category in both approaches (QSR: 47%, Delphi: 17%; Figure 5C), particularly the amount of produced biomass (QSR: 47%) and development of technology (QSR: 33%) (Table 6). The Delphi process also highlighted knowledge gaps around year-round production, scaling-up and consistent production quality versus price (Supplemental Table 4).

Relative PESTLE Sub-topic importance

With a total of 169 cases, the Environmental category was the main focus of the analyzed literature on seaweed cultivation (Table 6), with wider ecosystem effects and nuisance species representing the biggest concerns. In the second most studied (116 cases) Technical category, the amount of produced biomass (production at scale) was of highest interest. A lack of financing was the main economic constraint, whereas political dependence (close relation to other activities, e.g., wind parks) and stakeholders' perception provided additional weaknesses, which seem to be worsened by an apparent lack of governance.

Table 6. Constraints, negative impacts and knowledge gaps related to seaweed cultivation that were identified during QSR categorized into subtopics of the major PESTLE categories sorted by cumulative interest (CUM), calculated by summing up cases of the corresponding subtopic and PESTLE. Data provide information on numbers of studies addressed (cases) and their relative percentages toward the PESTLE or corresponding sub-category.

	Constraints		Negative impact		Knowledge gaps		CUM
PESTLE/ sub-category	cases	%	cases	%	cases	%	cases
ENVIRONMENTAL	**58**	**100**	**59**	**100**	**52**	**100**	**169**
Wider ecosystem effects/biological shift	8	13.8	18	31	16	30.8	42
Nuisance species	16	27.6	5	8	13	25.0	34
Water conditions	14	24.1	3	5	4	7.7	21
Emission/Absorption	2	3.4	9	15	9	17.3	20
Algal blooms			17	29			17
Invasion and gene flow	1	1.7	7	12	5	9.6	13
Substrates	2	3.4			2	3.8	3
Seasonality	10	17.2			1	1.9	11
Weather	2	3.4			1	1.9	3
Grazer	2	3.4			1	1.9	3
Data	1	1.7					1
TECHNICAL	**50**	**100**			**66**	**100**	**116**
Production	12	24.0			31	47.0	43
Technology	14	28.0			22	33.3	36
Nursery	8	16.0			4	6.1	12
Product quality	5	10.0			4	6.1	9
Harvest	3	6.0			3	4.5	6
Post harvest	5	10.0			1	1.5	6
Training	3	6.0			1	1.5	4
ECONOMICAL	**20**	**100**	**1**	**100**	**12**	**100**	**33**
Financing	9	45.0			6	50	15
Market	11	55.0	1	100			112
LCA					6	50	6
POLITICAL	**11**	**100**	**5**	**100**	**1**	**100**	**17**
Dependence	3	27.3	5	100			8
No support	6	54.5					6
ABS	1	9.1			1	100	2
Space	1	9.1					1
SOCIAL	**8**	**100**	**4**	**100**	**10**	**100**	**22**
Stakeholder	3	37.5			3	30.0	6
Jobs	3	37.5			2	20.0	5
Gender	2	25.0			2	20.0	4
Occupational health			2	50	1	10.0	3
Copying with climate change					2	20.0	2
Esthetical and Art			1	25			1
Network			1	25			1
LEGAL					**8**	**100**	**8**
Governance					7	87.5	7
Contaminant limit					1	12.5	1

Ecosystem services, disservices and resulting research questions

The analyses of the potential ES provided by seaweed aquaculture, considering constraints, negative impacts and knowledge gaps also revealed potential ecosystem disservices and open research questions. As presented in Figure 6, seaweed aquaculture was identified to be hindered mainly by technological and environmental constraints, including appropriate farming methods and equipment and suitable farming sites.

The resulting research questions were comprised of the following key areas and were used for the preparation of the subsequent science-policy workshop:

- **Site selection:** Which environmental parameters define a suitable site? How can impacts and conflicts derived from competition for space be minimized?
- **Scale of cultivation:** How does scale affect the provision of ES? At what scale do seaweed farms provide maximal ES and most economic benefit? How can site carrying capacity be quantified for seaweed cultivation?
- **Environmental impacts:** What are the environmental impacts and carbon footprints of large-scale seaweed farms? Can polyculture of seaweed provide more ES than monoculture at large scale? How can losses due to nuisance species/disease/pests be minimized?
- **Technology:** How can we improve the technological advancement of seaweed production? How can consistent biomass/product quality be

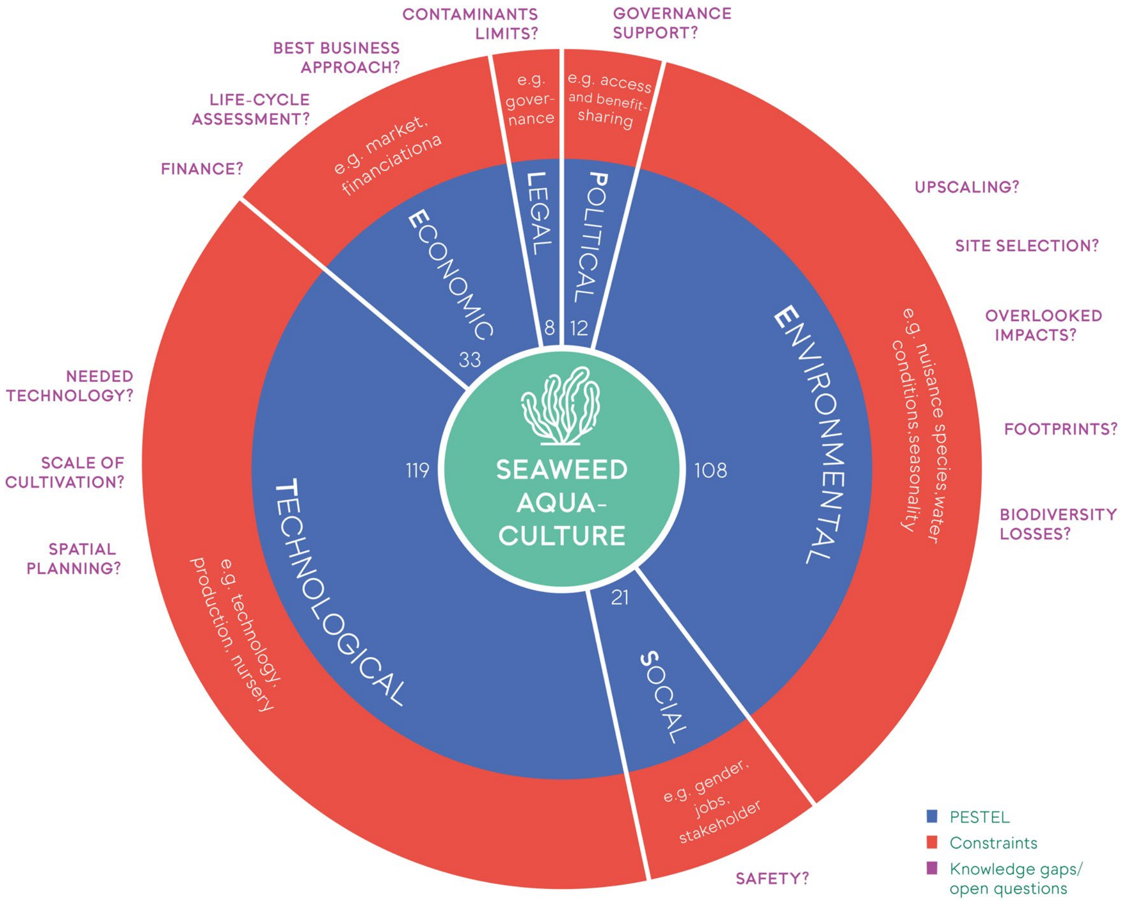

Figure 6. Conceptual model summarizing constraints, knowledge gaps and existing open questions (for each PESTLE category) of seaweed farming as well as potential ecosystem services and disservices of seaweed aquaculture, taken from Bermejo et al. (2022).

ensured, as well as food safety? How can seaweed production and processing become more energy efficient?

- **Economics:** What is the best business approach for different scales of seaweed cultivation in Europe? How can we better link production with processing?

Workshop results

During the science-policy workshop, four different key topics were identified and further discussed to address the knowledge gaps and the above-mentioned research questions. The results of the grouping and rating of knowledge gaps within each discussion topic are summarized below.

Topic 1: "Better understanding of biological and ecological components"

The top three knowledge gaps identified under this topic (Supplemental Table 5) included; (i) environmental response (e.g., life cycle control and biochemical composition of cultivated species, optimal site selection), (ii) handling of genetic diversity (e.g., biobank methodology, bio-protecting new species/strains) and (iii) definition of native species (e.g., local species list and alert system for invasive non-native species). Biotic interactions (i.e., between seaweed and other organisms, including higher trophic levels and epiphytes) and cultivation scaling up (i.e., control from laboratory to field) were also identified as knowledge gaps, although of less importance compared with the above.

Topic 2: "Better understanding of farming production systems for Europe, what is needed?"

The key knowledge gaps to support a more stable and sustainable European seaweed production system were: (i) the legal framework (including certification of algal products, food safety and social licensing), (ii) protection of genetic diversity (including genetic management, knowledge on domestication and biosecurity) and (iii) support of the farmer community (including licensing tools, cooperative businesses, toolkits, affordable hatcheries) (Supplemental Table 6).

Topic 3: "Better understanding of environmental impacts"

In terms of a better understanding of environmental impacts the workshop identified: (i) carrying capacity (including competition, nutrient impacts, and cumulative effects), (ii) societal impacts (including interpretation of social systems, and social perception) and (iii) environmental impacts (including sea-based vs. land-based impacts, need of impact assessment) as the main three issues (Supplemental Table 7).

Topic 4: "Better understanding of value chains, market acceptance, and economic scenarios. What knowledge is needed?"

In terms of topic 4, the main knowledge gaps were identified in the field as: (i) experience and support (e.g., managing expectations, sharing of good practices, toolkit for farmers), (ii) future scenarios (e.g., benefits for ecosystems, SDGs, relevance for the food system, job opportunities) and iii) bureaucracy (e.g., normalization, standardization, novel food legislation) (Supplemental Table 8).

Discussion

This study used a diverse array of methods to assess the ES provided by seaweed cultivation and identify the associated knowledge gaps and constraints. In the following the results of the study are discussed within the wider context of the sustainable upscaling of the seaweed cultivation industry in Europe.

Seaweed aquaculture on the rise

Seaweed aquaculture in Europe is clearly on the rise, as observed in the increasing number of publications identified in the present study, but also reflected in the numerous scientific projects, consortia and initiatives occurring in the wider European area over the past decades (e.g., Phycomorph, EU4Algae, Genialg, Seaweed for Europe, Seagriculture, GlobalSeaweedSTAR, food4future, Safe Seaweed Coalition (now known as Global Seaweed Coalition), SeaWheat, SeaStrains). The developing seaweed industry is also closely aligned with the EU Blue Economy Strategy (EC 2018), focusing on implementing a sustainable and circular bioeconomy in Europe (Araújo et al. 2021). Recent communications with the European parliament highlight the need to promote algae aquaculture to contribute toward several objectives of the EU Green Deal ("Strategic guidelines for a more sustainable and competitive EU aquaculture for the period 2021 to 2030" COM(2021) 236 final) and to set up 23 actions to unlock the potential of the EU algae sector ("Towards a Strong and Sustainable EU Algae Sector" COM(2022) 592 final). The recognized importance and rising need of seaweed biomass for different industry sectors, driven by the global demand for alternative food and feed, and more nature-based products, whilst addressing sustainable development goals (SDGs), has increased public awareness and transformed the perception of the importance of seaweed cultivation over the past few years.

EU demand for algae biomass and algae-based products is expected to increase by 2030 (reaching a value of up to EUR 9 billion), while current demand is mainly met by the importation of seaweed products (equivalent to EUR 554 million in 2016; EU COM(2022) 592 final). In the EU, seaweed aquaculture is finally starting to expand, diversify and produce novel products, but many technological, regulatory and market-related barriers persist (EU COM (2022) 592 final). The results of this study revealed that environmental and technical knowledge gaps, including production and processing technology, scaling-up, carrying capacity, genetic diversity and seed-stock source present key barriers and risks, which are associated with the development of the seaweed cultivation sector in Europe. While many of these barriers can be overcome through research and development, there is still a large discrepancy between the amount of scientific literature and actual seaweed biomass produced in Europe, compared to regions like Asia. The current increase in scientific literature may partially account for such discrepancies (Pan et al. 2018), but it might also signal that those financial resources are not being used most efficiently (i.e., by transferring the existing knowledge to practical applications). In this respect, the authors suggest that future project evaluation/success, not only focuses on the publication of research papers, but also emphasizes more practical results, like products, processes, capacity building and job creation. This could not only strengthen production, but could also help to foster the knowledge transfer between different stakeholders involved.

Regional strategies rather than overarching conceptualism

As revealed by the QSR, most seaweed cultivation is conducted in nearshore farms at small scale, whereas only a few larger-scale approaches have been recorded from Asian waters. Based on the observed regional discrepancies, primarily driven by the demand and needs of markets, but also by the differences in local seaweed species suitable for cultivation, there is a need for the development of targeted regional approaches rather than uniform cultivation to foster a sustainable growth in seaweed aquaculture. Based on the presented findings, in Asia and Latin America, where seaweed aquaculture has a longer tradition and higher production (Pérez-Lloréns et al. 2020), research is focusing on diversifying the industry by looking for new species to cultivate (Figure 3). In contrast, in Africa, Europe, North America and Oceania for example, most of the research has been focused on the optimization and specialization of a few seaweed groups for well-established markets, such as hydrocolloids. Due to their novelty in European Waters, the further implementation of seaweed farms and the choice of species will, therefore, require careful management and awareness.

Upscaling and shared resources (site selection)

As site selection was identified as a crucial factor for the upscaling of seaweed farms in Europe during the workshop, special care needs to be taken on this aspect, as competition for space (and related resources) can be one the most important constraints for the development of seaweed aquaculture in Europe. In addition to the identification of suitable environmental conditions, other legislative or technological aspects might also interfere, given competing interests related to marine spatial planning (e.g., by fisheries, shipping, and marine protected areas). In this respect, joint approaches with existing users (e.g., wind parks) can be a potential solution (Buck and Langan 2017), considering that synergies between both activities can reduce costs and make both activities more profitable. For example, the current "lighthouse projects" funded by the European Commission, OLAMUR and ULTFARMS, are investigating the feasibility of combining energy production and sustainable food production, whilst simultaneously providing ecosystem services. OLAMUR will include modeling studies for optimizing site selection for low trophic level aquaculture (seaweed and mussels) in exposed environments where wind parks are located (https://cordis.europa.eu/project/id/101094065). An additional commercial-scale seaweed farm, North Sea Farm 1, is being developed in a wind farm off the coast of the Netherlands for testing and improving seaweed farming and its potential to sequester carbon (https://www.northseafarmers.org/about-nsf1). Hence, several projects are underway to assess the feasibility of seaweed farming in wind parks and their capacity to reduce CO_2 emissions. These studies will contribute to a better understanding of the impact of scaling up seaweed production and will shed light on what new challenges will need to be addressed at commercial-scale. Furthermore, because data demonstrating the ecosystem services provided by seaweed cultivation in offshore wind parks are currently lacking, these studies will potentially be the first to demonstrate and quantify the provisioning of ecosystem services by seaweed cultivation in a multi-use context.

Ecosystem services- potential driver to evaluate and justify seaweed farms

The application of ES provides a powerful tool aimed at evaluating not only the potential commercial value, but also the environmental, social, political and cultural impacts of seaweed cultivation systems (Hasselström et al. 2018, Cotas et al. 2023). This holistic approach can be of great importance in predicting potential consequences related to seaweed farm upscaling and to justify their related investment costs. Considering that most likely seaweed farming will be carried out by private companies and these entities need to be financially sustainable, it is important to attribute a value to these ES. An adequate and justified financial compensation based on the provided ES can help to improve the reputation of seaweed farms and also strengthen the willingness to take risks and overcome the identified obstacles.

As recognized in the present study, however, there are still uncertainties of the ES themselves. Despite clear definitions of ES currently exist, there is a clear lack of understanding among the different parties involved in seaweed cultivation.

Consequently, there was often no clear evidence of ES provided in the literature and some aspects, such as cultural impact, were missing in the responses to the questionnaires during the Delphi process (possibly also because of the limited number of responses). In addition to cultural services, also technical, legal and economic constraints were lacking in the literature, most likely because "negative results" are not often published. This indicates that more communication is necessary among the different stakeholders to facilitate further valorization and analysis of the ecological and economic footprint of large-scale seaweed production. In this context, the presented approach combining CICES v.5 and PESTLE analysis provided a valuable tool to define and categorize ES in the seaweed cultivation sector.

Regarding the QSR, many research articles focused on the ES provided by seaweed aquaculture, yet did not consider the balance between the loss and the gain of ES produced by seaweed aquaculture. For instance, when assessing the role of seaweed aquaculture in carbon sequestration, the carbon sequestered by natural and healthy ecosystems was typically not considered. This can be especially relevant when there is competition for space and resources (e.g., light, nutrients) between seaweed aquaculture and natural populations (e.g., seaweed farms v.s. seagrass meadows or kelp forests). Further spatial planning and site selection criteria should consider these balances to promote a sustainable and ecological friendly seaweed aquaculture.

The present study highlights that seaweed cultivation can provide various ES to humanity. Next to the provisioning of food and hydrocolloids, seaweed cultivation can play an important role in regulating water quality and shaping its environment. Seaweed cultivation can serve as a nursery for the cultured stock, but also provide habitat and shelter for adjacent biota. Nevertheless, there is still a need to quantify the ES provided by seaweed cultivation, considering only very few studies were shown to have achieved this during our assessment. This is mainly due to a lack of quantitative evidence for some ES (e.g., blue carbon and role in C-sequestration), as well as a lack of understanding and consensus on the methods for quantifying ES (van den Burg et al. 2022).

Ecosystem disservices, risk and constraints

Besides all recognized positive aspects provided by seaweed cultivation, there are also several constraints and even identified negative impacts, which need to be considered. These potential negative effects or disservices range from potential alterations in hydrodynamics and provision of additional habitats due to the farm constructions, which can change the sedimentation levels and alter the adjacent community (e.g., the attraction of benthic fauna, demersal fishes and even birds and mammals) depending of farm size (e.g., Wood et al. 2017). Overall, the regulating aspects of the environmental category linked with seaweed farming seem to highlight this point. As current knowledge ranges from observed interactions with adjacent biota (e.g., microbial and seagrass communities) to predicted shifts in whole ecosystems (e.g., Xie et al. 2017). Thus, for example there is high concern among shellfish (mussel) farmers that upscaling of seaweed cultivation might alter the phytoplankton concentrations, which could also affect the mussel production (e.g., Bruhn et al. 2016; Aldridge et al. 2021). Overall, the environmental consequences of a further upscale of seaweed farms are uncertain. To overcome these uncertainties and allow a time-near reaction to potential threats, accompanying monitoring is urgently required to support the ongoing and emerging farming activities (e.g., Campbell et al. 2019).

Choice of taxa and cultivation approach

The current study revealed that the types and proportions of ES provided by seaweed cultivation differ depending on taxa. Therefore, to optimize the benefits provided by ES of different taxa, a polyculture approach might support a higher quantity and diversity of ES in Europe. In this respect not only different types of seaweeds, but also combinations with other aquatic organisms are possible, for example, co-cultivation or integrated multi-trophic aquaculture (e.g., IMTA) approaches, whereas later aims to recycle the waste especially produced by fed Aquaculture (Chopin et al. 2012).

A more diverse polyculture or crop-rotation/seasonal species approach might additionally also help to overcome certain weaknesses observed in monoculture practices (e.g., susceptibility to spreading diseases, nuisance species or environmental alterations, e.g., heatwaves). Certainly, adaptation measures for dealing with climate change will need to be deeply woven into any framework proposed for scaling up the seaweed cultivation industry in Europe, considering that a recent estimate suggests more than 25% of mariculture-producing nations will lose 40-90% of their current production potential by mid-century under the SSP5-8.5 scenario ('fossil-fueled development—Taking the highway' with no mitigation; Oyinlola et al. 2022).

At the large scale, seaweed aquaculture may alter the environment by providing climate regulation services and other ES related to nutrient cycling and sequestration, thus producing both positive and negative impacts on natural communities and ecosystem functioning at a global scale that are often difficult to predict (Campbell et al. 2019). In fact, given their high growth and carbon uptake rates, there is a current growing interest in seaweed aquaculture as a way to reach carbon net zero (Hughes et al. 2012; N'Yeurt et al. 2012; Laurens et al. 2020; Hurd et al. 2022; Ould and Caldwell 2022). Due to the complexity of the topic (e.g., Hurd et al. 2022, Gallagher et al. 2022, Troell et al. 2022, Paine et al. 2023) and many unknowns surrounding the potential environmental impacts, it is still questionable whether it will be feasible and successful at the scales necessary to reduce carbon emissions. Initial estimates suggest that it would be necessary to cover 9% (N'Yeurt et al. 2012) or even more (Hurd et al. 2022) of global oceans with seaweed farms to significantly reduce CO_2 emissions, accompanied by sinking the biomass in the deep ocean, which would require massive increases in investment and technology and could lead to major conflicts of interest regarding marine spatial planning. Moreover, it opens up the question - why discard a resource that can be used for food, feed, biostimulants and biomaterials?

Diversification in seaweed cultivation and regional approaches

Despite the high natural diversity among seaweed, only about 20 species are commercially cultivated in European waters. Given the rising interest in alternative protein sources (reviewed in Kim et al. 2019), new bioactive compounds, nutraceuticals, functional foods and the rising number of bioprospecting studies (a search in Scopus using bioprospecting + macroalgae or seaweed resulted in 11 studies from 2022 compared to 2 from 2012), it will only be a matter of time before new species will be tested for cultivation. A primary example is the species *Asparagopsis taxiformis*, which is now intensively studied and for which cultivation trials are underway after its potential for reducing methane emissions in ruminants was discovered (Kinley et al. 2016).

In fact, there is a growing need and interest to further explore and use regional seaweed diversity to overcome legal issues (e.g., Nagoya protocol) and avoid issues of introducing non-native species. The spread of some seaweeds has caused environmental issues, affected native biota and in some cases (e.g., *Undaria pinnatifida*) even led to alterations of whole benthic systems. In this respect, there is a current need to document and protect local seaweed species and to potentially also implement necessary monitoring and restoration programs to avoid further depletion of wild stocks (Cottier-Cook et al. 2023). Moreover, the handling of genetic diversity needs to be organized in terms of cultivable strains by improving biobank methodology and bio-protecting new species/strains. Recent programmes (e.g., GlobalSeaweedStar) and new initiatives (e.g., SeaStrains Network) have paved the way to provide guidelines and protocols, as well as, international exchange and networking to promote biosecurity (Cottier-Cook et al. 2022) and protect biodiversity within the framework of seaweed cultivation.

Moreover, considering the known high seaweed diversity present in European waters and the recent innovations in cultivation approaches and processing technologies, it is most likely that the given number of commercially usable species will increase. Nevertheless, due to their novelty in European Waters, the further implementation of large-scale seaweed farms will require careful management. In this respect, seaweed cultivation in land-based structures (e.g., in Recirculating Aquaculture Systems) might gain more importance in the near future by allowing a higher level of control over the cultivation conditions.

Methodological limitations

The lack of engagement in the Delphi process suggests the need for a better communication base amongst stakeholders. There was a clear imbalance between the responsiveness level of academia and all other stakeholders, even the industrial ones. The Delphi process envisions an exchange of information that benefits from a diversity of knowledgeable stakeholders. The QSR is aimed at rapidly retrieving information to get a state-of-the-art overview of the topic concerned. Inevitably, it does not allow for an in-depth analysis of the papers. The QSR made use of scientific publications, knowledge and expertise covered in the grey literature (not controlled by the peer-review approach) is therefore not represented in this method. The combination of QSR and the Delphi process was chosen to overcome these weaknesses.

Current progress and outlook

Many projects and initiatives are currently developing regulations and guidelines for the safe and sustainable expansion of the European seaweed cultivation sector. For example, the licensing toolkit developed by Seaweed for Europe and the EU4Algae working group on seaweeds, where networking sessions with algae farmers, webinars with latest development on seaweed cultivation, knowledge transfer to seaweed farmers and on-site trips for journalists and policy makers were among the supported activities. Furthermore, a report on the development of a European strategy for safeguarding seaweed genetic diversity is underway in the SeaStrains Project. Several projects funded by the European Commission are also progressing to assess the feasibility of scaling-up scale seaweed farms in wind parks. The newly established Seaweed Academy is also an excellent example of capacity building and education within the seaweed farming industry (www.seaweedacademy.co.uk).

In conclusion, we identified ES provided by seaweed aquaculture, as well as knowledge gaps, constraints and negative impacts. We also identified how these services contribute to the UN SDGs. While many ES are provided, the type and extent is taxa specific. Many unknowns still exist in relation to the up-scale of seaweed aquaculture, and as the industry grows, management strategies will need to be developed to prevent the introduction of new pests and pathogens, the release of waste and plastics into the oceans, a reduction in the genetic diversity of wild seaweed populations and/or negative interactions with other stakeholders and sea-users.

In our opinion, therefore, we must proceed following a risk management approach, stressing the need for more technical and scientific evidence, particularly at large-scale, to support a progressive, but steady development of this industry in the EU. It is also imperative that this is supported by an appropriate framework of regulations and policies that integrate climate change adaptation, biosecurity and biodiversity conservation to facilitate the sustainable development of this industry, whilst maximizing the resulting ES to humanity.

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ORCID

Buschmann AH http://orcid.org/0000-0003-3246-681X
Fricke A http://orcid.org/0000-0003-1188-0114
Capuzzo E http://orcid.org/0000-0002-6055-6970
Bermejo R http://orcid.org/0000-0003-3838-9093
Hofmann LC http://orcid.org/0000-0002-2307-3750
Hernández I http://orcid.org/0000-0002-8024-2813
Pereira R http://orcid.org/0000-0003-4925-4418
Van den Burg S W K http://orcid.org/0000-0003-3849-482X
Pereira T http://orcid.org/0000-0002-4217-6069
Cottier-Cook E J http://orcid.org/0000-0002-1466-6802

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