EKLIPSE REPORT

FEB 2022

What is the state of knowledge regarding the potential of macroalgae culture in providing climate-related and other ecosystem services?

Requested by

DG-Mare

REPORT

"What is the state of knowledge regarding the potential of macroalgae culture in providing climate-related and other ecosystem services? "

February 2022

EKLIPSE EXPERT WORKING GROUP MACROALGAE

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Version	prepared by	Data	Status
1.0	EWG	10/02/2022	For public review

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1. GLOSSARY

Term	Definition	Key References
Ecosystem services	In CICES ecosystem services are defined as the contributions that ecosystems make to human well-being, and distinct from the goods and benefits that people subsequently derive from them	www.cices.eu; Haines-Young, R. & M.B. Potschin, 2018
Land-based cultivation	cultivation of macroalgae on land	
Transitional	cultivation of macroalgae in estuarine or brackish waters	
Near-shore, sheltered	cultivation of macroalgae in marine waters <50m water depth & <3 nautical miles distance to shore	Bak et al. (2020)
Near-shore, exposed	cultivation of macroalgae in marine waters >50 meters depth & <3 nautical miles from shore	Bak et al. (2020)
Offshore	>3 nautical miles from shore	Bak et al. (2020)
Green Deal		https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en
European Blue Bioeconomy		https://ec.europa.eu/info/research-and-innovation/research-area/environment/bioeconomy/blue-bioeconomy_en
Blue-Growth		https://s3platform.jrc.ec.europa.eu/blue-growth

Trade-offs	A situation in which you balance two opposing situations or qualities	https://dictionary.cambridge.org/pt/dicionario/ingles/trade-off
Blue Carbon		https://www.iucn.org/resources/issues-briefs/blue-carboN
EMFF	European Maritime and Fisheries Fund	https://ec.europa.eu/oceans-and-fisheries/funding/european-maritime-and-fisheries-fund-emff_en

2. BACKGROUND AND OBJECTIVES

There is growing awareness of and interest in the potential of macroalgae present in coastal ecosystems, including cultivation, to provide a wide range of solutions and mitigations to anthropogenically-induced problems. There is strong evidence that macroalgae aquaculture can potentially mitigate climate change (e.g. via uptake of carbon dioxide), protect coastlines, reduce local biodiversity loss, improve water quality, among other ecosystem services. Nevertheless, there are still many constraints and knowledge gaps that need to be overcome, as well as potential negative impacts or scale-dependent effects (e.g. farm size or type of aquaculture) that need to be considered before macroalgae cultivation in Europe can grow successfully and sustainably.

This Eklipse request for knowledge synthesis (CfR.5/2020/1) aims to explore and map existing knowledge and identify knowledge gaps and trade-offs, to inform future development of macroalgae culture strategies and policies. Furthermore, more knowledge is needed to evaluate impacts in terms of water, energy, land and sea use, changes in sedimentation rates and structure of local ecological communities, potential pollution and risk of releasing non-native invasive species into the environment. This additional knowledge can contribute to the development, promotion and implementation of adequate and timely policy frameworks.

The requester, DG Maritime Affairs & Fisheries, Unit for Maritime Innovation, Marine Knowledge (DG MARE), is contemplating the development of an EU Algae Strategy. This strategy will take into consideration the multiple areas where macroalgae cultivation can contribute to the Green Deal as well as the importance of the overall algae sector for the development of a sustainable European Blue Bio-economy. The successful development of this strategy requires that the knowledge gaps, constraints, and potential negative impacts related to macroalgae cultivation are identified in order to advise, through DG MARE, the development of relevant research activities under the next EMFF and Horizon Europe programmes. Therefore, the requester posed the following questions:

- What is the state of knowledge regarding the potential of macroalgae culture in providing climate-related and other ecosystem services?
- Are there specific knowledge gaps to be addressed before harvesting this potential?

To answer these primary questions, the Expert Working Group (EWG) on Macroalgae was established. The EWG has been meeting remotely weekly since February 22nd, 2021. The EWG received an introduction to the Eklipse call, a presentation on the requests and needs of the requester and the accompanying Document of Work, and a summary of the available methods by the Methods Expert Group (MEG). The EWG then selected four co-chairs to lead the subsequent meetings. After several discussions with the MEG, the EWG agreed on the methods to be used and was organised into two groups, with each group focusing on one of the two chosen methods. The details on the choice of methodology and expected outcomes are described below.

3. METHODOLOGICAL FRAMEWORK

To achieve the objectives formulated above, a combination of the following two methods was followed: A Multiple Expert Consultation with Delphi Process and a Quick Scoping Review (QSR). These methods were conducted in parallel, rather than sequentially. A first round of questions was sent to selected experts as part of the Delphi Process, and then the EWG proceeded with the QSR. The use of the two methods helped to provide a more comprehensive answer to the request than the use of a single method, as shown in **Table 1**.

Table 1: Relationships between the request **objectives** and proposed **knowledge synthesis methods**.

Questions	Quick Scoping Review	Delphi Process
What is the state of knowledge?	• Provides synthesis of relevant literature • Generates knowledge base to hold against results from Delphi	• Identify and prioritise ecosystem services considered relevant • Identify constraints for up-scaling • Identify trade-offs and negative impacts
Are there specific knowledge gaps?	• Evident if no literature is found in targeted areas of interests	• Collects expert opinions on knowledge gaps • Formulate pathways to fill these gaps

The QSR focused on peer-reviewed literature, and the Delphi process captured the most recent and up-to-date views of experts from key sectors, including science, business and NGOs. Therefore, while QSR provides a robust view on published literature and evidence, Delphi covers views of not only scientists, but also other societal actors with practical and experience-based knowledge on the key issues in macroalgae cultivation.

To analyse the outcome of both approaches we adopted the PESTEL approach (Basu 2004), classifying the papers according to external key factors (Environmental, Technical, Economic, Political, Social, Legal). Ecosystem services (ES) were categorised based on the CICES 5.1 classification (Haines-Young and Potschin-Young 2018).

4. DELPHI

4.1. METHODOLOGY

The Delphi process is an iterative technique for collecting information using expert consultation in a structured manner in order to produce forecasts and evaluate complex problems. This method was originally described by Dalkey and Helmer (1963) and has since then been adapted to the fields of ecology and biology (Mukherjee et al. 2015) and many others. Because of the iterative and controlled nature of the process, which remains anonymous, it is a rigorous approach to eliciting expert knowledge. The main benefits of using the Delphi Process are that it is relatively rapid and low cost, rigorous, repeatable and transparent. The drawbacks of the method are that it can be time consuming for the experts and there can be some bias from experts with strong opinions, if this is not managed carefully.

4.1.1. ADAPTING THE DELPHI METHOD FOR THIS ASSIGNMENT

The Delphi process was adapted to address the questions raised by the EWG on macroalgae cultivation. We identified at least 130 experts from 40 countries, 15 of which were EU countries, to participate in three rounds of questioning. The geographic distribution of experts was global but considering that the requester is interested in knowledge gaps surrounding macroalgae cultivation in Europe, the EWG agreed on including approximately 70% of the experts from Europe and 30% of the experts from elsewhere throughout the world. The experts invited were a mix of representatives from academia, industry, and organisations with particular interest in the marine environment, such as private environmental organisations or other stakeholders (tourism, fisheries, etc.). It was decided to aim for an approximate ratio of 3:3:2:2 representation from academia, industry, NGOs, and other marine organisations, respectively.

The work document prepared for the Delphi Process is presented in **Annex 1**. In addition to a general introduction and the actual questions for round 1, it also includes 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 between activity sectors.

The first round of the Delphi process adopted open questions, very much aligned with the questions provided by the Document of Work for the Macroalgae culture request (February 2021).

The first round of questions used to assess expert opinions using the Delphi process was sent out to 104 experts from academia, industry, NGOs and other marine organisations. We received responses from 22 participants. Their responses were analysed and consolidated into a revised questionnaire for the second round of expert opinions.

For the second round of the Delphi process, we provided a list of Ecosystem Services, knowledge gaps, and negative impacts or trade-offs identified in the first round and asked the respondents to rank them in order of importance or severity (see **Annex 1** for specific questions used in the second round). We received responses from six experts in the second round. The results obtained from the Delphi process are presented below.

Even though the initial methodology planned for three rounds in the Delphi process, after the first round, the EWG experts decided, based on the low response (6% after 2 rounds), that two rounds were enough. This decision was also validated by the Eklipse methods experts, considering the results from the first round, the planned questions for the second round and the time frame available.

4.2. RESULTS

4.2.1. CHARACTERIZATION OF RESPONDENTS

The majority of responses to the first questionnaire were from representatives of academia or research (**Fig. 1**). Only four respondents were representatives from industry, and only single responses were obtained from NGOs, professional associations or international organisations. Among experts from academia and industry, the most dominant focus areas fell into the categories of macroalgae cultivation, macroalgae hatchery/nursery, and macroalgae processing (38%, 28%, and 18%, respectively; **Fig. 2**). Combined, these focus areas accounted for 84% of the responses. Only 5% of experts focused on marketing and sales, while focus areas such as macroalgae genetic characterization and breeding, education, management and conservation of brown algae, kelp forest studies, seaweed diversity/phylogeography, macroalgae diversity, macroalgae genetics, macroalgae horticulture, were represented by only 2.5% of participants. Over 40% of experts in the first round of the Delphi process were from Europe, but a global representation was present among the participants (**Fig. 3**). Nearly half of the experts had expertise in near-shore seaweed cultivation (either sheltered or exposed), while 21% had expertise in land-based cultivation and 15% had experience in offshore cultivation (**Fig. 4**). Very few experts had experience in cultivation in ponds or in transitional waters.

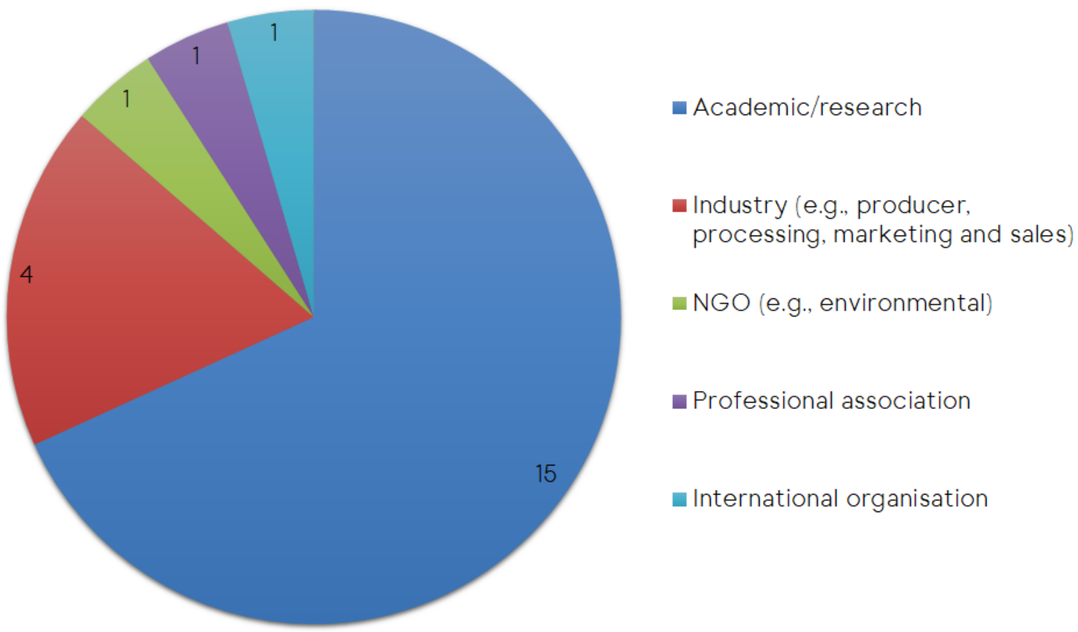

Fig. 1 Distribution of experts in the different sectors related to seaweed cultivation that responded to the first round of the Delphi questionnaire

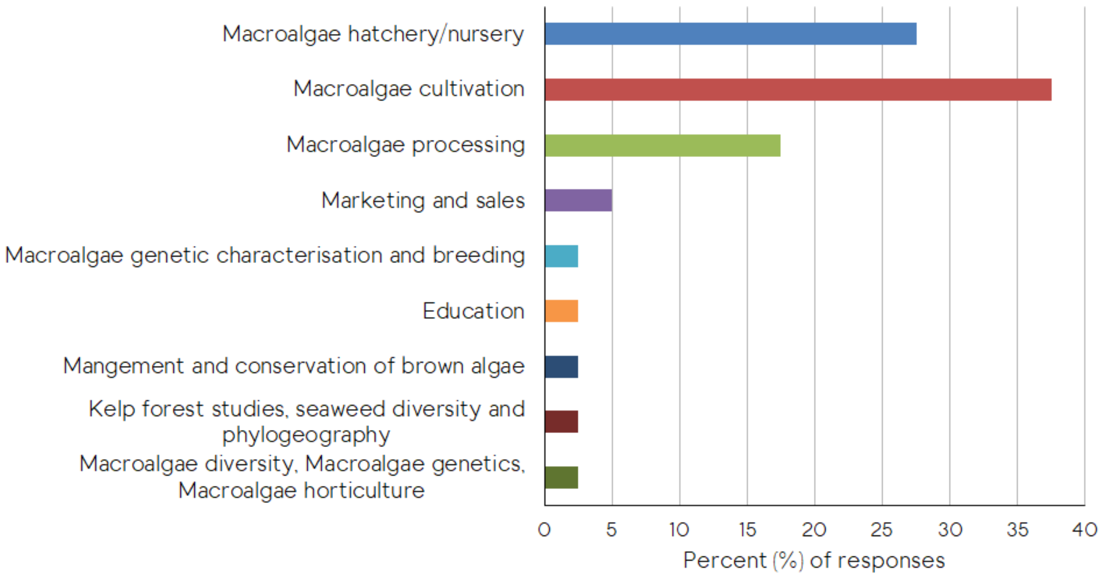

Fig. 2 Focus areas of experts from academia and industry that responded to the Delphi questionnaire

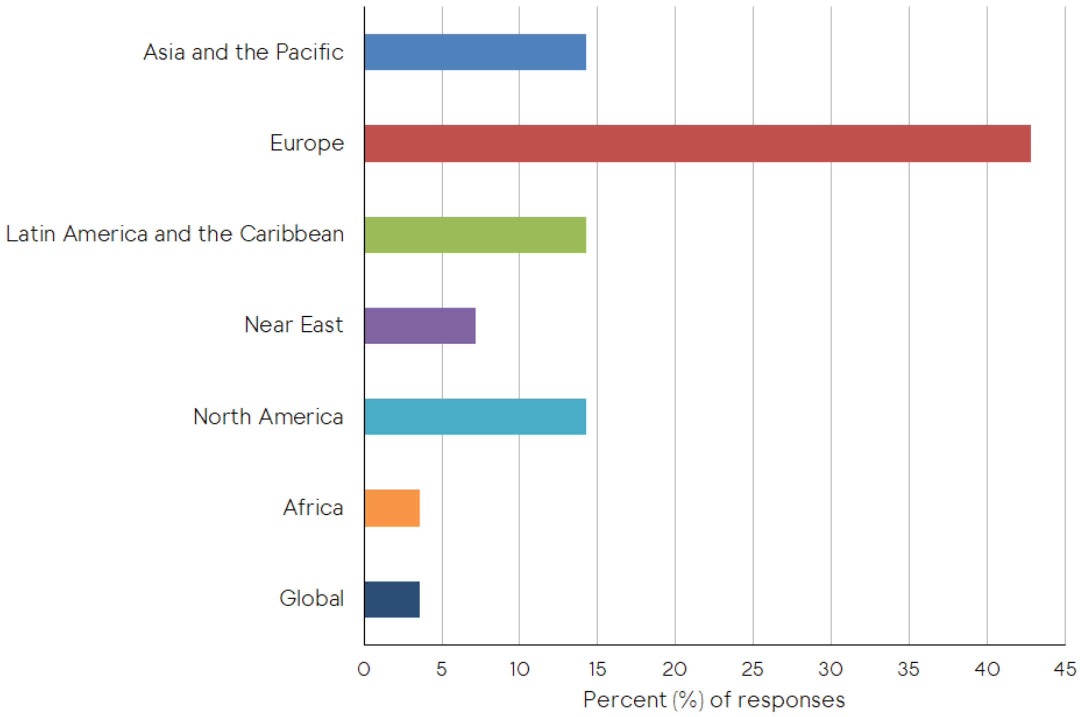

Fig. 3 Regional distribution of experts that participated in the Delphi questionnaire

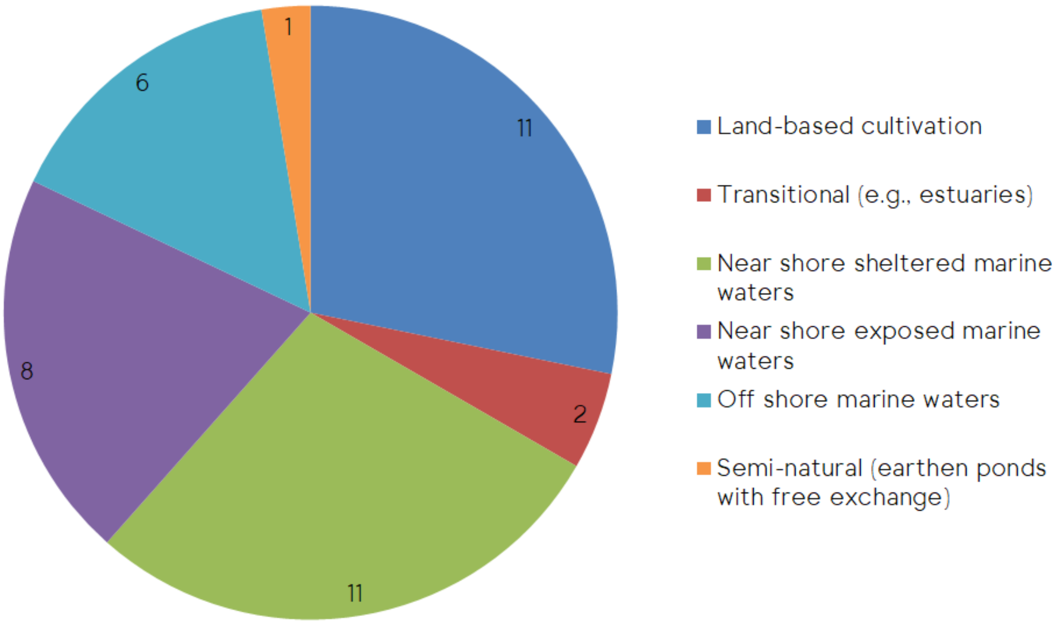

Fig. 4 Distribution of work experience in terms of types of seaweed cultivation among experts that participated in the Delphi questionnaire

4.3. MAIN ECOSYSTEMS SERVICES IDENTIFIED BY THE DELPHI RESPONDENTS

According to the responses of the Delphi questionnaire, 85 % of Ecosystem Services (ES) identified by the experts for seaweed cultivation fell within the "Regulation and Maintenance" category, based on the CICES 5.1 Classification (**Fig.5**). Only 12% of ES identified were classified in the "Provisioning" category, and 3% were classified as "Cultural".

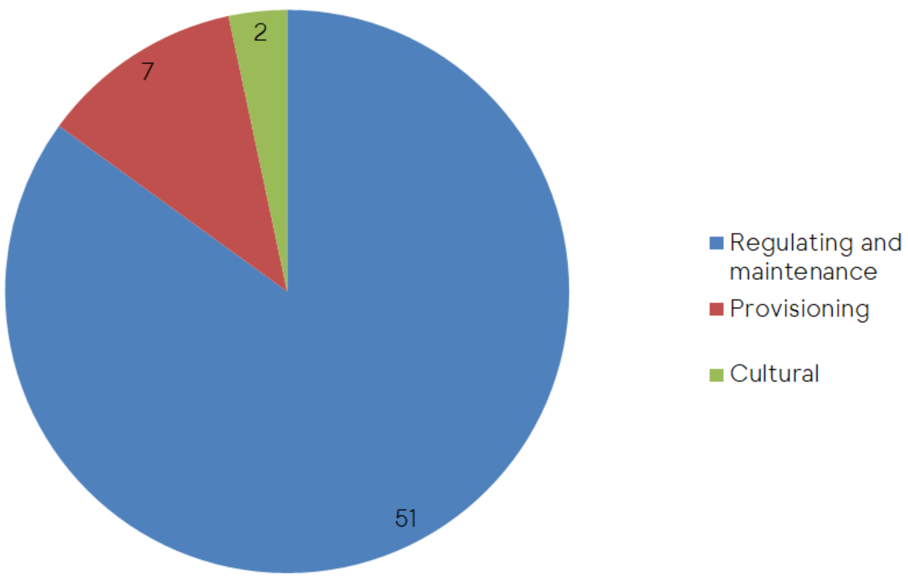

Fig. 5 Overview of relevant ecosystem services (general categories based on the CICES 5.1 classification) according to the expert responses to the Delphi questionnaire

A further breakdown of the responses (**Fig.6**), still using CICES 5.1 classification, shows that the **most referred ES** provided by seaweed cultivation belong to the following classes: "Regulation of chemical composition of atmosphere and oceans (code 2.2.6.1) " and "Filtration/ sequestration/ storage/ accumulation by microorganisms, algae, plants, and animals (code 2.1.1.2)" both with 17%, followed by "Maintaining nursery populations and habitats, including gene pool protection (code 2.2.2.3) with 13%.

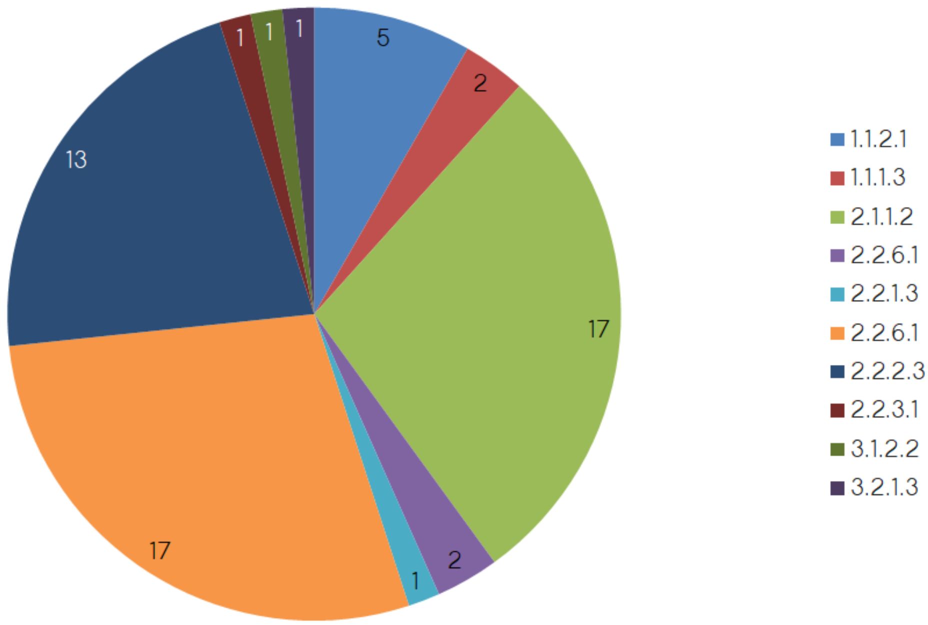

Fig.6 Overview of specific ecosystem services provided by seaweed cultivation according to the expert responses to the Delphi questionnaire. Numeric codes correspond to CICES 5.1 Classification , as follows, Section (Class): **1.1.2.1** - Provisioning (Fibres and other materials from cultivated plants, fungi, algae and bacteria for direct use or processing (excluding genetic materials); **1.1.1.3** - Provisioning (Cultivated plants (including fungi, algae) grown as a source of energy); **2.1.1.2** - Regulating & Maintenance (Filtration/sequestration/storage/accumulation by microorganisms, algae, plants, and animals); **2.2.1.3** - Regulating & Maintenance (Hydrological cycle and water flow regulation (Including flood control, and coastal protection); **2.2.6.1** - Regulating & Maintenance (Regulation of chemical composition of atmosphere and oceans); **2.2.2.3** - Regulating & Maintenance (Maintaining nursery populations and habitats (Including gene pool protection)); **2.2.3.1** -Regulating & Maintenance (Pest control (including invasive species)); **3.1.2.2** - Cultural (Characteristics of living systems that enable education and training); **3.2.1.3** - Cultural (Elements of living systems used for entertainment or representation).

During the second round of the Delphi process, in reply to Question 1, it was then asked to rank the top 5 ecosystem services: "From the list of **Ecosystem Goods and Services (ES)** presented below, please select the 5 that you feel are most important and rank them from 1 to 5, where 1 is the most important and 5 is the least important of the options selected".

The average ranking is presented below (**Table 2**), whereas a higher score indicates higher importance. These results confirm only partially those of the first round. In fact, while in the first round the most referred ES were within the "Regulating & Maintenance" (85%) category, in the second round the most important ES related to "Provisioning" (in 2 of the top 3). ES such as recreation and tourism, education and training, and coastal protection were ranked as the least important by the experts (**Table 2**).

Table 2: Average scores of the ES, for Question 1, ranked from higher to lower importance, according to the respondents selected option. Individual ranking was set from 1 to 5, whereas higher score indicates higher importance.

Ecosystem service	Average score
Macroalgae grown for food (including hydrocolloids)	3.8
Regulation of water quality (including eutrophication, bio- mitigation, bioremediation)	3.2
Macroalgae grown for feed	2.7
Maintaining nursery populations and habitats (including gene pool protection)	2.0
Carbon sequestration/storage/accumulation by macroalgae	1.3
Climate regulation (CO2, carbon cycle, DMS, other)	1.3
Macroalgae grown as a source of energy	0.5
Pest and disease control	0.2
Coastal protection (erosion, wave reduction, flood control)	0.0
Characteristics of living systems that enable education and training	0.0
Elements of living systems used for recreation and tourism	0.0

4.3.1. CONSTRAINTS IDENTIFIED BY THE DELPHI RESPONDENTS

Participants also responded to the question regarding the main constraints that need to be resolved before upscale significantly macroalgae cultures. The responses from the first round were grouped according to the PESTEL analysis (**Fig. 7**). Three categories equally stand out: legal (e.g. safety regulations), economic (e.g. lack of demand for seaweeds in many countries) and technological (e.g. production in large scales) and represented almost 70% of the total. According to the responses received, the less important constraints were related to social and environmental issues, representing 9,6% and 7,7%, respectively, of the total identified. Political constraints (e.g. political development and permitting) were identified in eight responses and represented 15,4% of the total.

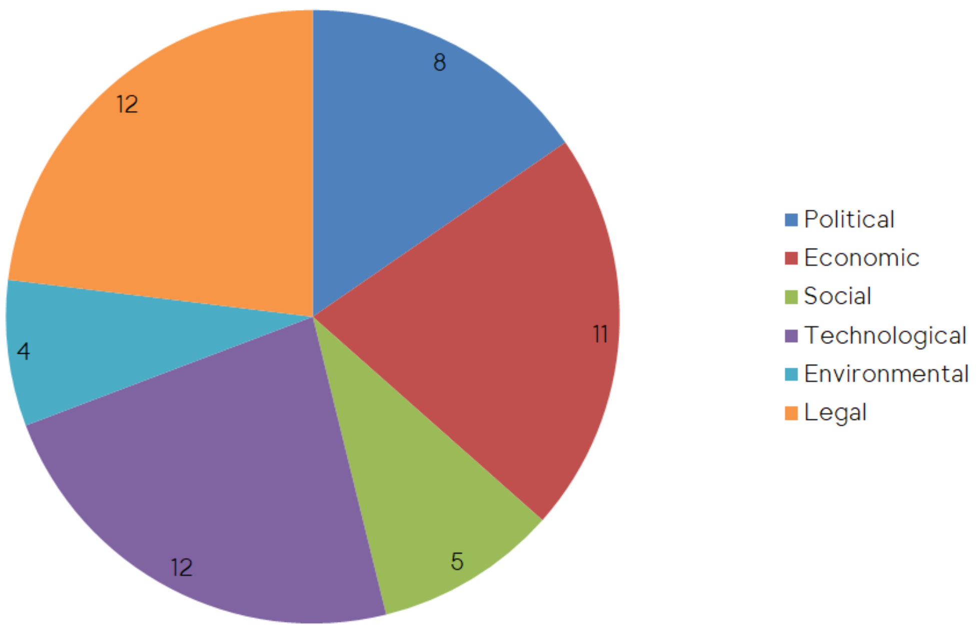

Fig.7 Distribution of constraints identified during the first round of the Delphi process among the PESTEL categories.

4.3.2. NEGATIVE IMPACTS ACCORDING TO DELPHI RESPONDENTS

When asked what negative impacts or trade-offs upscaling macro-algae cultivation may lead to, particularly when it comes to ES, experts provided diverse responses, which are summarised below in **Table 3.**

Table 3 Clustering of examples of potential negative impacts or trade-offs of seaweed cultivation provided by experts that participated in the first round of the Delphi questionnaire.

Negative impacts provided by experts

Excessive nutrients removal (e.g. compromising other ecosystem functioning, impacting the food web)
Carbon capture (e.g. excessive removal and impact on final destination, such as sinking)
Destruction of habitats (e. g. shading; clearing up the seafloor using anchor/stakes)
Decrease species diversity/biodiversity
Spreading diseases and pests
Impacts on tourism (e.g. plastics, casted biomass, visual impact, etc.)
Decrease water quality (e.g. pollution during farming operations, materials, debris, etc.)

In the second round of the Delphi process, the participants were asked to rank the negative impacts: "From the list of **negative impacts** or trade-offs that may result from upscaling of macroalgae cultivation (as identified in the previous round of questions) please select the five that you feel are most critical and rank them from 1 to 5, where 1 is likely to be the most severe and 5 is likely to be the least severe of the options selected".

The weighted scores associated with each impact show that 'Conflict with other users/uses' was the most important negative impact of macroalgae cultivation, identified by the experts, followed by 'Unknown environmental impacts' (**Table 4**). Physical damage (resulting from the farm structure) and reduction of water flow were ranked as the least important (**Table 4**).

Table 4: Negative impacts, identified by the experts during the first round of the Delphi process and ranked during the second round

Potential negative impact or trade-off	Average score
Conflict with other users/uses (at land or sea)	3.17
Unknown environmental impacts (e.g., on deep sea, benthic and pelagic ecosystems)	2.50
Mismatch in supply and demand of biomass	2.00
Shifts in seaweed genetic diversity	2.00
Pollution (e.g., plastics)	1.50
Negative impacts on ecosystem biodiversity	0.83
Aesthetics	0.83

Over exploitation of the environment	0.83
Water flow reduction	0.67
Physical damage (e.g., damage to the sea floor resulting from the farming structures, anchors, stakes, etc.)	0.67

4.3.3. MAIN KNOWLEDGE GAPS ACCORDING TO DELPHI RESPONDENTS

In reply to the question: "What are the **knowledge gaps** on macroalgae cultivation (e.g., processing and marketing), that would need to be addressed in order to upscale it and enhance its delivery of ES?", the respondents to the questionnaire mentioned a number of topics, which the EWG grouped into categories listed in **Table 5**. It should be noted that the provided answers were often not formulated as a knowledge gap; instead, the experts mentioned one or more terms related to a knowledge. The EWG have refrained from reformulating the answers, to avoid incorrect interpretation. All knowledge gaps, or hints at knowledge gaps, were categorised using the PESTEL framework in **Table 5.** The results presented in **Fig. 8** show that the highest number of knowledge gaps identified by the experts fell within the 'Technological' category, followed by 'Economic'.

Table 5: Knowledge gaps identified during the first round of the Delphi process, with associated PESTEL category and count (number of experts that identified each specific knowledge gap).

Term related to a knowledge gap	PESTEL Category	Total counts
Biofouling (1), Density (1), Drying/stability/pre-processing (4), Consistent production quality (2), Strain improvement for quality and consistency (2, Farming technology (1), Year-round crop to enable uptake of nutrients and achieve a stable secondary ecosystem around fish farms (1), Mechanization (1), Land-based cultivation (1), Evaluate near- and offshore farm grounds (1),	Technological	15
Suitable price (1), Transparency market prices (1), Business case (2), Upscaling of farms to km^2 size (1), Production in large-scale (2), Moving offshore for more space (1), Detailed market information (1)	Economic	9
CO_2 credits, Biodiversity credits (1), Change politics (1), Set standards for heavy metal maximum values (1), Mechanisms for valorisation of ecosystem services (1)	Political	4

Ecosystem carrying capacity (3), Insight into scale-effects (1),	Environmental	4
Training of young scientists (1), Direct links between farmers and processors (1)	Social	2

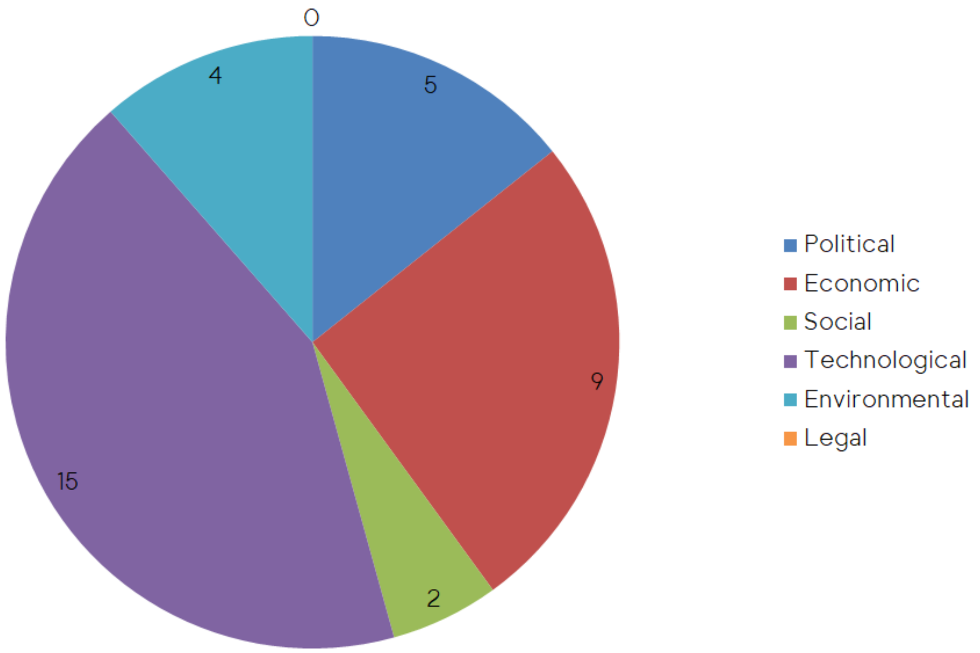

Fig.8 Knowledge gaps identified during the first round of the Delphi process grouped by PESTEL categories (as in Table 5). Note that there is no knowledge gap related to the legal category.

In the second round, the participants were asked to rank the knowledge gaps based on importance: "From the list of knowledge gaps presented below, please select the five that you feel are most important and rank them from 1 to 5, where 1 is the most important and 5 is the least important of the options selected".

The weighted scores of knowledge gaps (**Table 6**) suggest to confirm the importance attributed to the **Technological Knowledge Gaps**, such as "farming technologies", and "technologies for macroalgae processing", followed by **Market Data** (including sub-categories belonging to the Economics, Technological and Social divisions of a PESTEL analysis). **Economic** and **Political** aspects are the following categories of knowledge gaps and **Environmental** assumes less importance in the ranking according to the respondents, with 'Training' as the least important.

Table 6: Knowledge gaps identified during the first round and ranked during the second round of the Delphi process

Knowledge gaps category	Average Score	Sub-categories
Farming technologies	2.3	Strain improvement
		Ensure consistent production quality
		Develop mechanisation; Technologies for further cultivation approaches
Technologies for macroalgae processing	2.0	
Market data	1.67	Adequate value-chain connections
		Detailed market information
		Adequate price
Economic data	1.5	Appropriate business cases
		Information on valorisation of ES
Politics	0.8	NA
Data obtained from "real" macroalgae farming	0.8	Appropriate scale of production
		Appropriate spatial planning for farming sites
Environmental data	0.3	Nutrient uptake/bioremediation
		Biodiversity impact
		Occurrence/impact of nuisance species
Certification	0.3	CO_2 footprint
		Food safety
		Ecosystem provisioning
Training	0.0	NA

It is interesting to notice the lower importance attributed to Knowledge Gaps concerning **Environmental Data**, when compared to **Technological** and **Economic** knowledge. Even though the question specifically asked for knowledge gaps that could help to upscale macroalgae production and enhance its ES deliveries, and that several ES directly related to "Regulation & Maintenance" and "Provisioning", many responses were related to knowledge gaps that can be considered in the **Technological** and **Economic** categories.

In reply to the request to **provide some possible means (actions and/or key players) to address critical knowledge gaps**, the following suggestions were provided by the respondents:

- *"**Authorities that provide permits** for farming, connecting them in the EU to harmonise the rules"*
- *"Enable **large scale test sites** by connecting the projects to independent institutions following the effects"*
- *"**Include Lloyds to learn about the risks**. De-risking in all aspects is essential for further upscaling"*
- *"**Seaweed cultivation must enter the political agenda to create funds** that will support farmers developing novel technologies and automation in production and processing. This will ensure consistent production quality."*
- *"The **EU should be a key player in funding research and technology specifically in addressing these knowledge gaps**, both through general and industry pointed financing actions, including more COST actions."*
- *"Totally **dependent which country you live**, no point providing this as state agencies, dept. of marine or Universities are responsible."*

Once again, in this case the EWG decided not to rephrase the respondents' answers, in order to avoid any bias. In this case, it is worth noting that even though the main knowledge gaps are in the Technological category, many of the suggestions are related to Political issues, either through funding decisions, licensing aspects (namely country harmonisation) and planning.

5. QUICK SCOPING REVIEW

5.1. METHODOLOGY

A Quick Scoping Review (QSR) is a systematic and objective study of evidence from scientific literature, which aims to provide an informed conclusion on the volume and characteristics of an evidence base and a synthesis of what that evidence indicates in relation to a question. In order to reduce the time and expense of production, this method does 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). In the present study, a quick scoping review was conducted (Collins et al. 2015) to identify peer-reviewed English language scientific journal articles, addressing ecosystem services provided by macroalgal cultivation. The scoping review was carried out to summarise the current state of the knowledge and identify potential constraints and knowledge gaps. For this purpose, documents were screened in three different steps (identification, screening, eligibility; **Fig.9**).

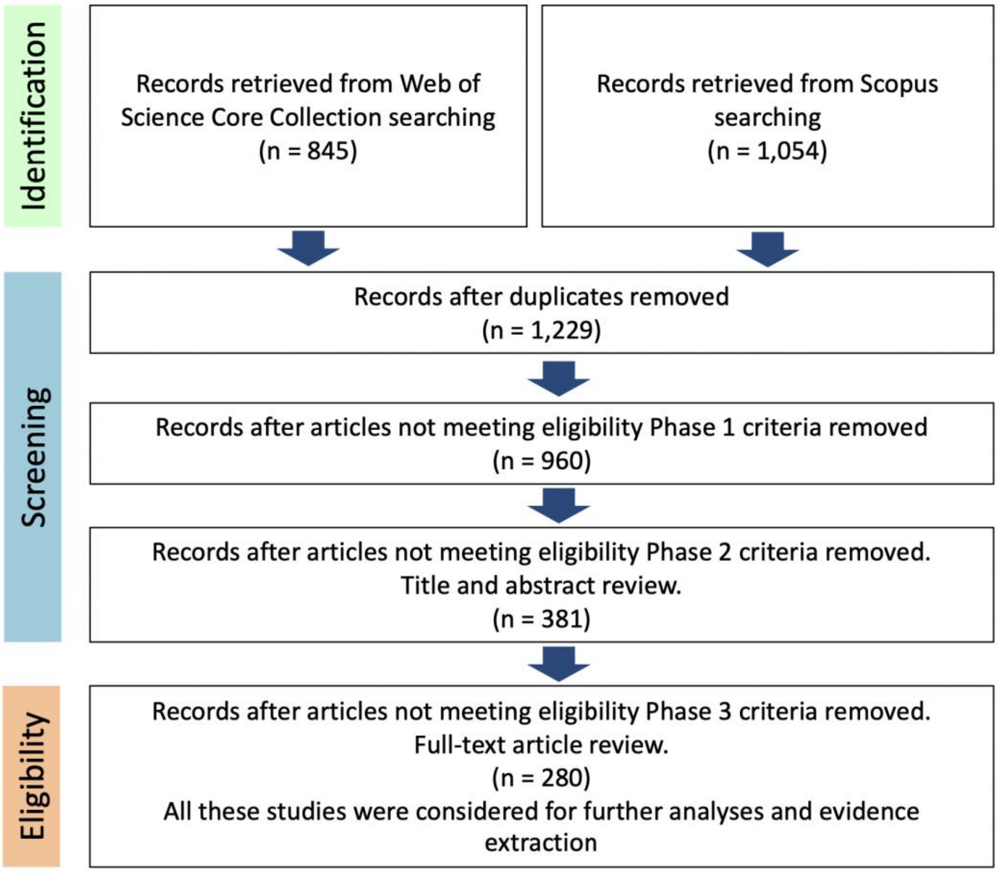

Fig.9 Diagram showing the different steps during the quick scoping review and the number of manuscripts that were finally considered eligible.

5.1.1. STEP 1 – IDENTIFICATION

In the first step, we conducted a structured search of the scientific literature. A preliminary exploration of the literature, based on 5 primary keywords (Macroalgae, Seaweed, Cultivation, Farming, Aquaculture) and 11 secondary keywords (climate change, invasive species, impacts, arsenic, bromine, ecosystem services, greenhouse, value chain, biosecurity, carbon, bioremediation) using the web search engine Google Scholar resulted in 442 papers. However, a further broader search was carried out, due to concerns of potentially missing important papers, as result of keyword restrictions and the general nature of ecosystem services. Consequently, new keywords were defined, based on six combinations of the primary terms "macroalga" and "seaweed", and the secondary terms "cult*", "farm*" and "aquaculture", whereas quotation marks were used for combination and search to reduce the number of unrelated literature. The search was conducted in parallel in Scopus and Web of Science (WoS) database, on 16th June 2021. Data was compiled in Mendeley (reference management software) and duplicates were removed using the software, resulting in a total of 1229 entries (**Table 7**).

Table 7. Outcome of literature search of the six keywords in Scopus and Web of Science (WoS) database in June 2021. Amount of totals include data set after software and subsequent manual duplicate removal.

Keyword	Scopus	WoS	
Seaweed aquaculture	136	227	
Seaweed farm*	363	266	
Seaweed cult*	620	348	
Macroalgae* aquaculture	15	15	
Macroalgae* farm*	22	18	
Macroalgae* cult*	103	96	
Total duplicates (by software check)	1259	970	
Total	**1054**	**845**	**= 1899 => 1229**

5.1.2. STEP 2 – SCREENING

The resulting entries were sorted in an Excel spreadsheet with macros, containing information on bibliography type, author, title, DOI, publication year and abstract. All articles were sorted and screened according to **formal criteria** defined in an exclusion/inclusion table (**Table 8 Phase 1**) identifying 960 articles to be assessed in Phase 2. All articles fulfilling the formal criteria of phase 1 were randomly assigned and assessed by the different experts in the working group, who decided based on **title and abstract** and defined criteria (**Table 8 Phase 2**) whether the article should be included or excluded. After Phase 2, the 381 remaining articles were assessed again following the same criteria that in Phase 2, but based on the full text, which resulted in a total of 280 articles. These 280 articles provided the base of the following analytical part of the QSR and are listed in

References forming the base of the QSR. To avoid potential bias by individual decisions during Phases 2 and 3, the eligibility of each article was assessed by two experts. In case of disagreement a third expert assessment was conducted to determine if the article was eligible or not.

Table 8. Summary of exclusion and inclusion criteria used in phases 1 (formal criteria) and 2 (title and abstract review) of the Quick Scoping Review

Exclusion criteria	Inclusion criteria
Phase 1: Formal criteria	
Non-English	English
Before 2000 or after 06/2021	Between 01/2000 and 06/2021
Non original articles	Peer-reviewed original articles
Non available in SCOPUS or WoK	Available in SCOPUS or WoK

Exclusion criteria	Inclusion criteria
Phase 2: Title and Abstract / Phase 3: Full text	
No seaweed aquaculture	Seaweed aquaculture
Laboratory experiments (<100 L)	Aquaculture systems (>100 L)
Focus on functions	Focus on services
New methodologies or products	Assessment of actual services
Weak link with seaweed aquaculture	Risk & Disservices of seaweed aquaculture
Optimization EOs techniques	Spatial and temporal assessment of seaweed aquaculture
Description of associated biodiversity to seaweed aquaculture	Studies on the biotic interplay related to seaweed aquaculture

5.1.3. PHASE II - CLASSIFICATION

To provide a general insight of the volume and characteristics of the evidence found in the scientific literature, the eligible articles were classified in different categories, included as columns in the Excel spreadsheet with macros. These categories addressed the classification of the different articles, according to 1) species, 2) country, 3) scale, 4) sector, 5) PESTEL analysis, 6) aquaculture type, 7) study protocol, 8) farm size; as well as their contribution, to different ecosystem services (ES: 9) provisioning, 10) regulating and maintenance, 11) cultural; based on CICES Classification v 5.1. (Haines-Young and Potschin-Young 2018). Corresponding cells were partly to be filled via pre-formulated drop-down menus to ease classification, whereas a separate specification column allowed the expert to provide additional information. For the review findings, the columns 12) knowledge gaps, 13) identified constraints, 14) disservices, 15) disservices comments and 16) expert notes were also provided. An overview of all categories with corresponding subcategories are presented in **Annex 2.** Scientific papers selected for inclusion from Phase 1 were randomly assigned to experts of the working group and classified. A synthesis of the literature reviewed using the QSR method is presented in the following section. Results refer to QSR literature provided in the **References**.

5.2. QUICK SCOPING REVIEW DATA SYNTHESIS

The geographic regions that dominated the studies included in the QSR were Asia (30%), Europe (24%) and Oceania (23%). Fewer studies were conducted in Latin America (11%) and Africa (7%), and fewer still in North America (4%) (**Fig.10**). Only 3% of the studies screened conducted a global analysis of seaweed cultivation.

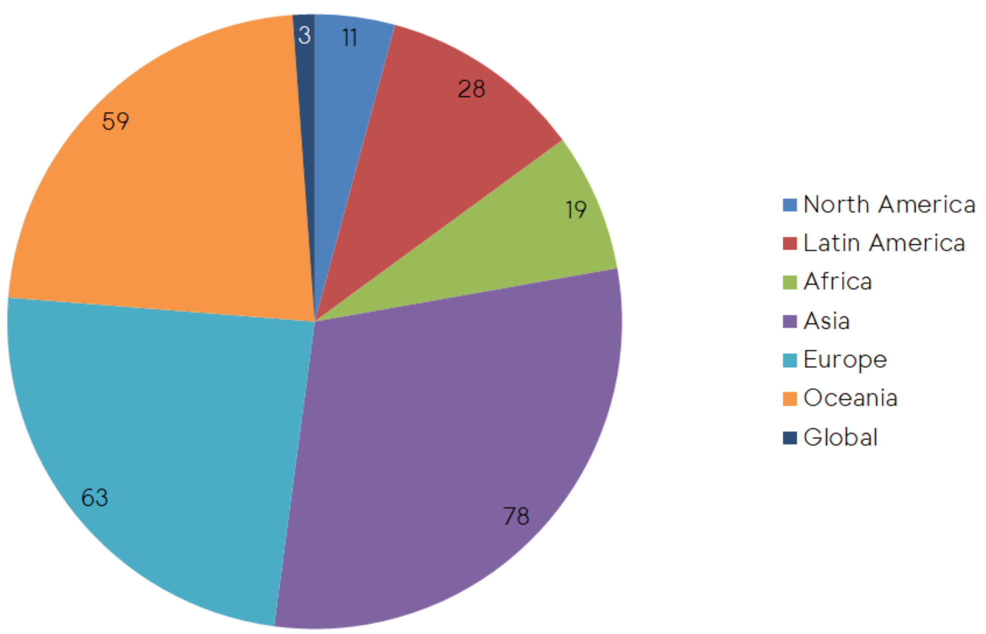

Fig.10: Geographic regions investigated in the studies identified in the QSR

Of the 280 studies reviewed in the QSR, 213 considered a total of 37 macroalgae genera comprising about 77 species. In studies focusing on European Waters, we found 17 different species, with *Saccharina latissima* as the most highly studied (61% of the considered studies), followed by *Laminaria digitata* (13%) and *Alaria esculenta* (9%). Nevertheless this has to be interpreted with caution, due to potential taxonomic mismatches. Species names were validated according to the taxonomic data base algaebase (Guiry and Guiry 2022). For analysis, the different seaweed taxa were categorised into the following six taxonomic groups:

i) ***Porphyra/Pyropia*** (about three genera and four species: ***Pyropia*** *sp.*, ***Porphyra*** *umbilicalis*, ***Neopyropia*** *tenera*, *N. yezoensis*).

ii) **Eucheumatoids** (two genera comprising about three species: ***Eucheuma*** *denticulatum*, ***Kappaphycus*** *alvarezii*, *K. striatus*).

iii) **Gracilarioids** (two genera comprising about 18 species: ***Gracilaria*** *birdiae*, *G. bursa-pastoris*, *G. cervicornis*, *G. changii*, *G. chilensis*, *G. cornea*, *G. conferta*, *G. domingensis*, *G. edulis*, *G. gracilis*, *G. parvispora*, *G. tenuistipitata*, *G. textorii*, *G. tikvahiae*, *G. vermiculophylla*, ***Gracilariopsis*** *chorda*, *G. lemaneiformis*, *G. longissima*).

iv) **Ulvoids** (one genus comprising about 10 species: ***Ulva*** *australis*, *U. clathrata*, *U. compressa*, *U. intestinalis*, *U. lactuca*, *U. ohnoi*, *U. prolifera*, *U. pseudorotundata*, *U. reticulata*, *U. rigida*).

v) **Kelps** (order Laminariales- eight genera comprising about 11 species: ***Alaria*** *esculenta*, ***Ecklonia*** *maxima*, *E. cava subsp. stolonifera*, ***Laminaria*** *digitata*, *L. farlowii*, ***Lessonia*** *trabeculata*, ***Macrocystis*** *pyrifera*, ***Nereocystis*** *lutkeana*, ***Saccharina*** *latissima*, *S. japonica*, ***Undaria*** *pinnatifida*).

vi) **Other** (21 genera about 31 species: ***Anadyomene*** *stellata*, ***Asparagopsis*** *armata*, *A. taxiformis*, ***Blidingia*** *sp.*, ***Caulerpa*** *lentillifera*, *C. racemosa*, ***Chondracanthus*** *teedei*, *C. chamissoi*, ***Codium*** *fragile*, *C. taylorii*, ***Chaetomorpha*** sp., ***Cladophora*** sp., ***Derbesia*** *tenuissima*, ***Dictyota*** *ciliolata*, ***Furcellaria*** *lumbricalis*, ***Gayralia*** sp., ***Gelidium*** *amansii*, ***Hypnea*** *musciformis*, *H. pseudomusciformis*, ***Padina*** *australis*, ***Palmaria*** *palmata*, ***Rhizoclonium*** *sp*, ***Sargassum*** *aquifolium*, *S. fusiforme*, *S. liebmannii* , *S. platycarpum*, *S. siliquosum*, *S. wightii*, ***Spirogyra*** sp., ***Turbinaria*** *conoides*, ***Ulothrix*** sp.*)*.

Figure 11 shows the number of studies from the QSR that provided data on each seaweed taxon. About one third (30.5%) of the studies focused on kelps, mainly represented by the genus *Saccharina (S. latissima, S. japonica)*, followed by Gracilarioids (20.7%), mainly represented by the genus *Gracilaria*, and the Eucheumatoids (17.9%), presented by 3 species, followed by the Ulvoids and *Porphyra*/*Pyropia*. Some studies did not specify a seaweed taxa, in which case they were assigned to the category "other."

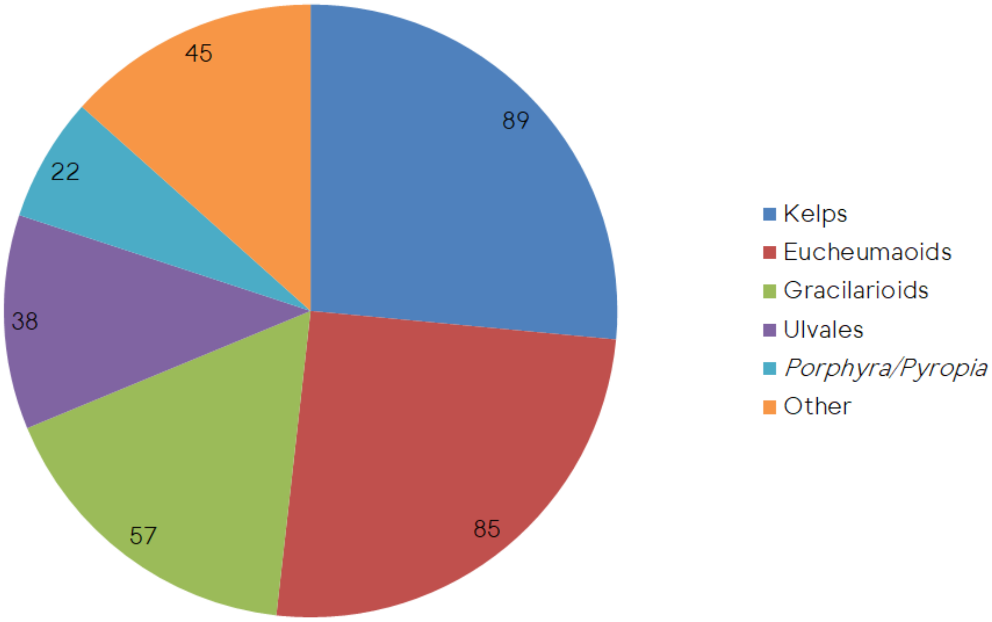

Fig.11: Percentage contribution of **seaweed taxa** within the literature identified in the QSR (n =213)

5.2.1. SEAWEED FARMS

The majority of studies (58%) were conducted in nearshore, sheltered waters. Land-based seaweed cultivation was represented in 12% of studies, while offshore seaweed cultivation was represented in 6% of studies and exposed, nearshore sites only represented 2% of studies reviewed in the QSR (**Fig.12**).

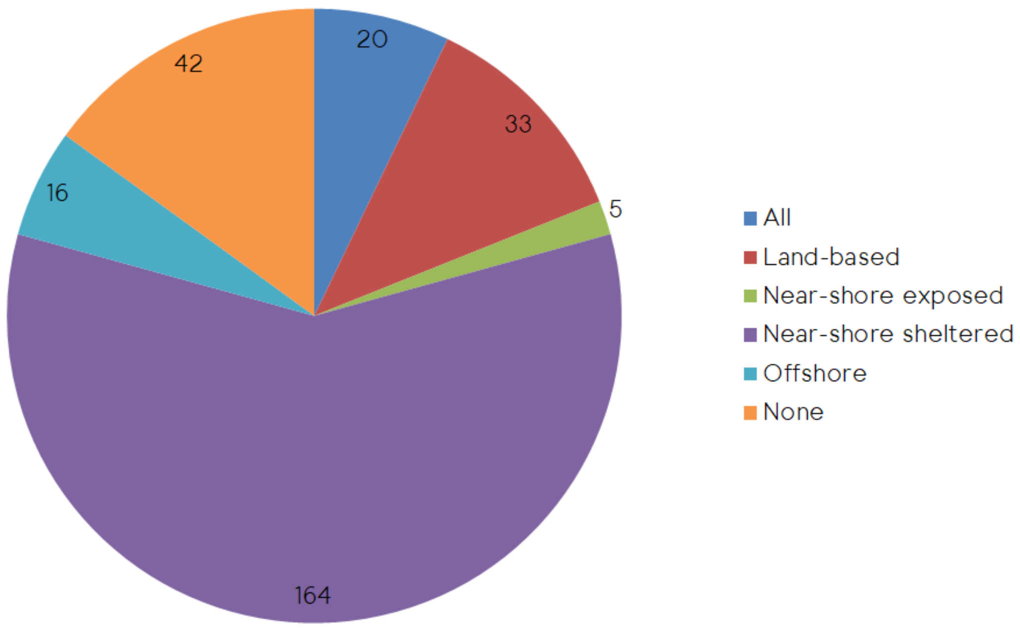

Fig.12 Overview of the **types of seaweed cultivation** that were identified during the Quick Scoping Review. See the Methods Section for the definition of each cultivation.

In many studies (36%), the scale of the study was not reported. Among studies where the scale of seaweed cultivation was reported, 23% were on a pilot scale, 18% were considered large,15% were considered small, and 8% were considered intermediate scale (**Fig.13**).

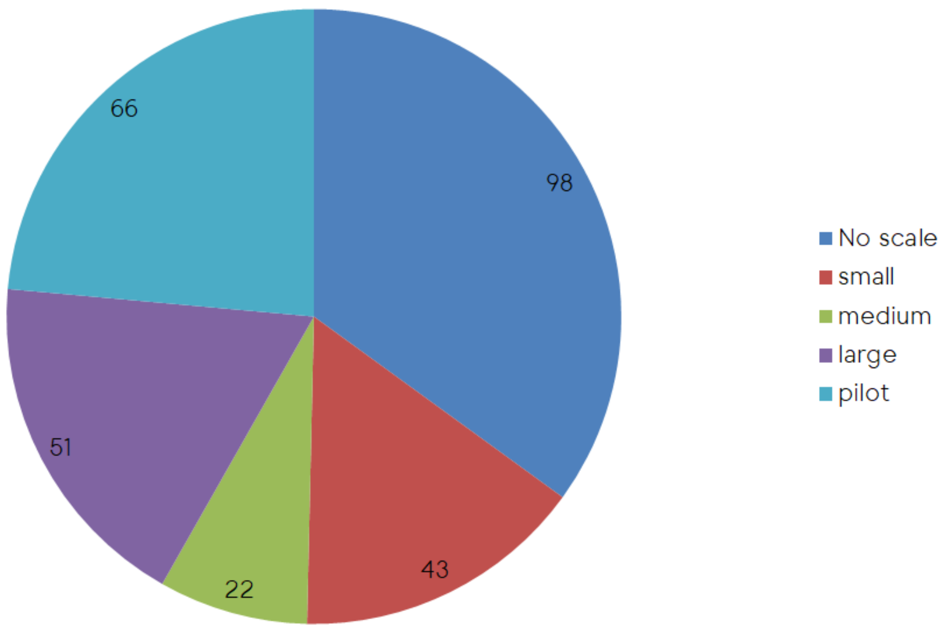

Fig.13 Overview of the **scales of seaweed cultivation** identified during the Quick Scoping Review (n=280). See the Methods Section for the definition of each scale.

5.2.2. ECOSYSTEM SERVICES

Ecosystem Service Classification

The QSR resulted in 214 studies giving evidence of ecosystem services provided by seaweed cultivation. Please note that in some studies evidence for more than one ecosystem services were found. 'Provisioning' (49%) and 'Regulation and Maintenance' (45%) services were identified as the two main categories of ecosystem services provided by seaweed cultivation, but cultural ecosystem services were also represented (**Fig.14**).

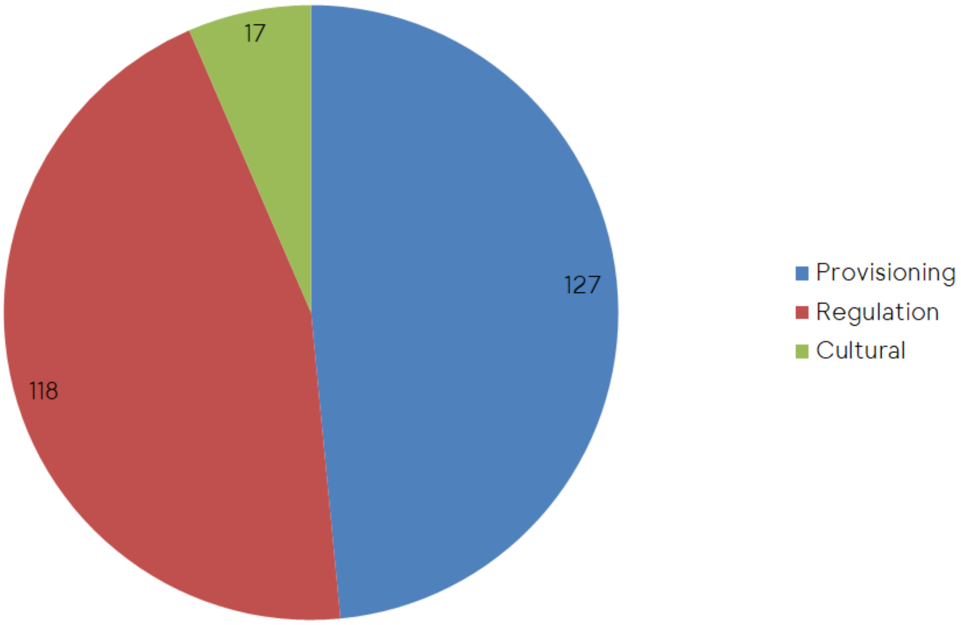

Fig.14 Overview of the number of studies identified through the Quick Scoping Review that provided evidence of ecosystem services provided by seaweed cultivation based on the CICES classification.

Within the 'Provisioning' services classification, biomass was the most common (36%) ecosystem service provided by seaweed cultivation, followed by hydrocolloids (30%), food (28%), and lastly feed (6%; **Fig.15**).

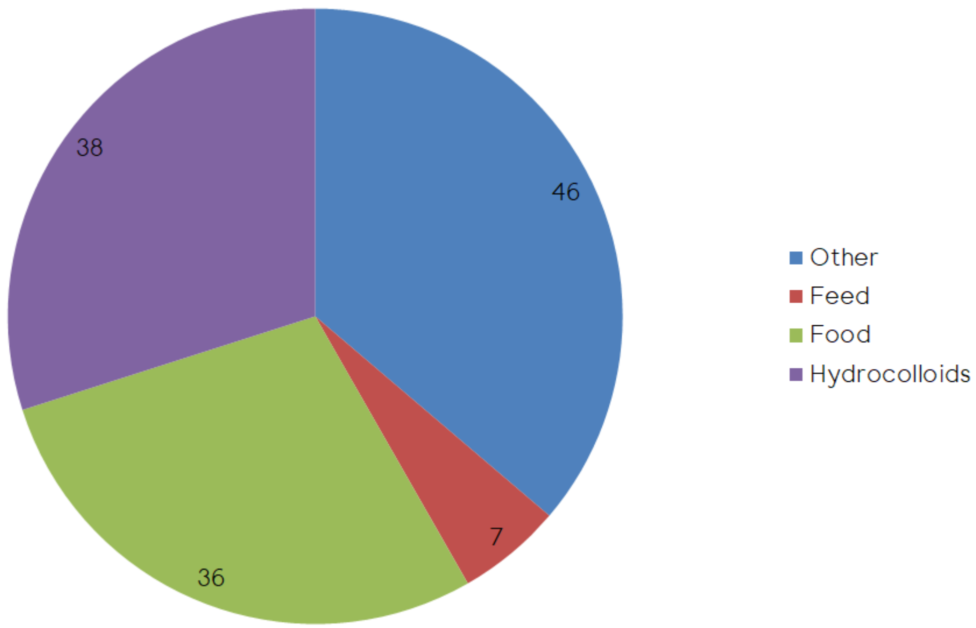

Fig.15 Overview of the types of Provisional Services provided by seaweed cultivation and the number of associated studies based on the Quick Scoping Review.

The QSR showed that the ecosystem service most often provided by seaweed cultivation within the 'Regulation and Maintenance' classification was water quality improvement. The QSR also identified studies (31%) that provided evidence of diverse types of biological regulation and climate regulation (16%; **Fig.16**).

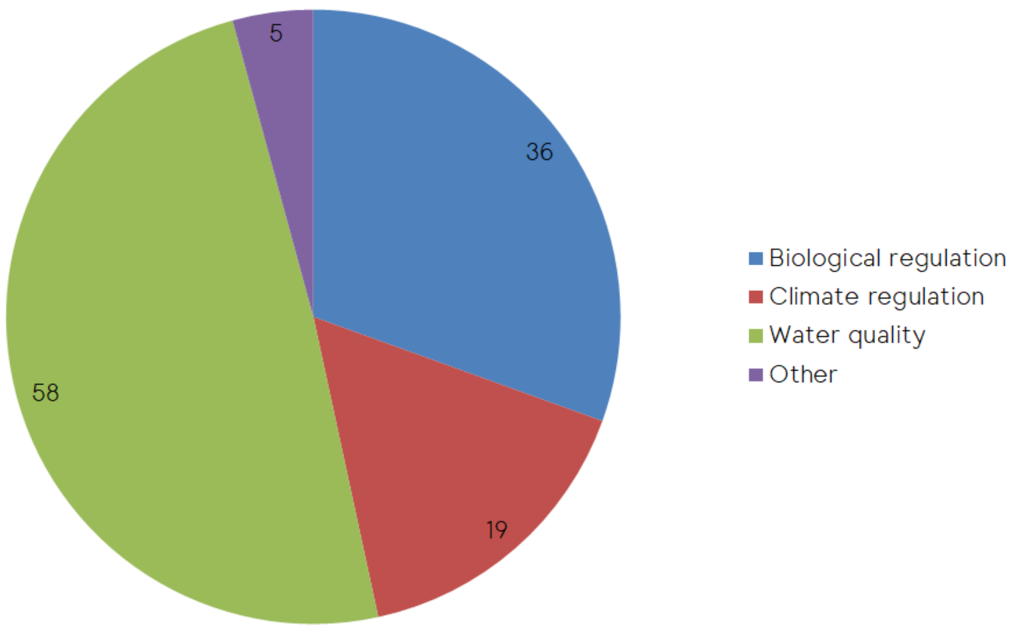

Fig.16 Overview of the types of Regulating and Maintenance Services provided by seaweed cultivation and the number of associated studies based on the Quick Scoping Review.

Results of the QSR showed that the 'Cultural' services provided by seaweed cultivation include education and learning, recreation and tourism and social welfare (**Fig.17**). The educational/learning aspect of seaweed culture has provided a viable livelihood source in marginalised coastal communities of countries such as the Philippines, India or Indonesia (269, 273, 105). The activity can promote inclusiveness and gender equality and the studies have pointed out increased awareness to conserve coastal ecosystems. However, there are also constraints (e. g. marketing limitations, farm ownership, climatic risks) to further develop seaweed farming industries. Some of these constraints can be successfully overcome with the help of specific training workshops and technical guidance (195). Seaweed farming has also been perceived as a tourism product in developing countries (103) to enhance the socioeconomic status of the community. Macroalgae culture can have social meaning beyond the economic activity in coastal communities, particularly when the activity dignifies the role of women in society (43). Evidence of seaweed cultivation providing the ecosystem services of scientific knowledge and symbolic aesthetics could only be found in single studies, suggesting that more studies are needed to assess the cultural ecosystem services provided by seaweed cultivation.

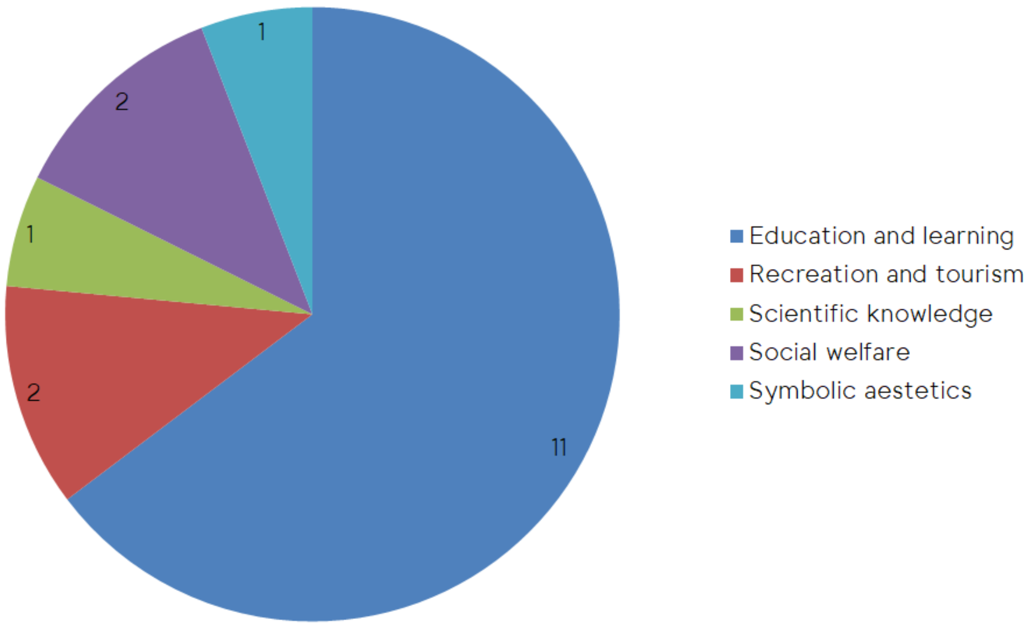

Fig.17 Overview of the types of Cultural Services provided by seaweed cultivation and the number of associated studies based on the Quick Scoping Review.

Analysis of the ecosystem services provided by seaweed taxa (**Fig.18**) showed that kelp, as well as the Gracillariods and the Ulvoids, as strongest represented taxa, were mainly considered to regulate water quality (29%, 42% and 41% of total ES, respectively), besides providing food and biomass used for other purposes, whereas the Eucheumatoids were mainly considered for hydrocolloid production (45% of total ES) .

This suggests that the different groups of taxa seem to provide different ecosystem services in different proportions, and therefore a monoculture on a large-scale would not provide the greatest amount and diversity of ecosystem services. Rather, a combination of different species grown at scale could provide the greatest diversity and number of ecosystem services in Europe.

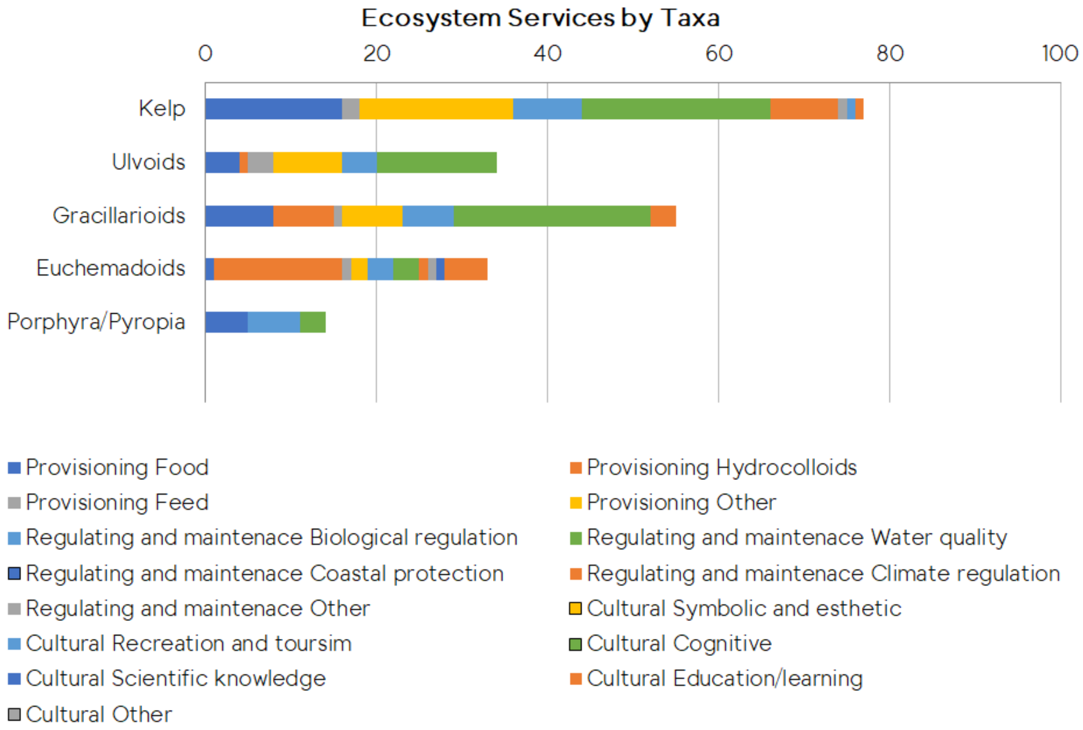

Fig.18 Ecosystem services (classification and service type) provided by different groups of seaweed taxa based on results from the QSR. The x-axis shows the number of studies that showed evidence of ecosystem services provided by each taxa.

Ecosystem Services and the United Nations Sustainability Goals

If the variety of ecosystem services provided by seaweed cultivation based on the results of the QSR are considered within the context of the United Nations Sustainable Development Goals (UN 2015), it is evident that many of the UN SDGs are addressed by seaweed cultivation (**Fig.19**). Most notably, goals 14 (life below water), 11 (sustainable cities and communities) and 12 (responsible production and consumption) are most often addressed by seaweed cultivation. More specifically, seaweed cultivation contributes to the target to prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution and to increase scientific knowledge, develop research capacity and transfer marine technology within

SDG 14. The bioremediation services provided by seaweeds also closely link to SDG 6 (clean water and sanitation), considering the interconnections between marine, estuarine and fresh-water systems and that bioremediation of marine waters can contribute to sustainable management of water resources and supplying access to safe water and hence unlocking economic growth and productivity. The target to protect the world's cultural and natural heritage via sustainable tourism within SDG 11 is also addressed. Additionally, seaweed cultivation can contribute to goals 2 (zero hunger), 3 (good health and well-being), 7 (affordable and clean energy), 10 (reduced inequalities), and 13 (climate action). Even the collaboration and efforts by the EWG for this request, including sharing knowledge and expertise, can be considered a contribution to global partnerships and sustainable development (SDG 17, target 17.16).

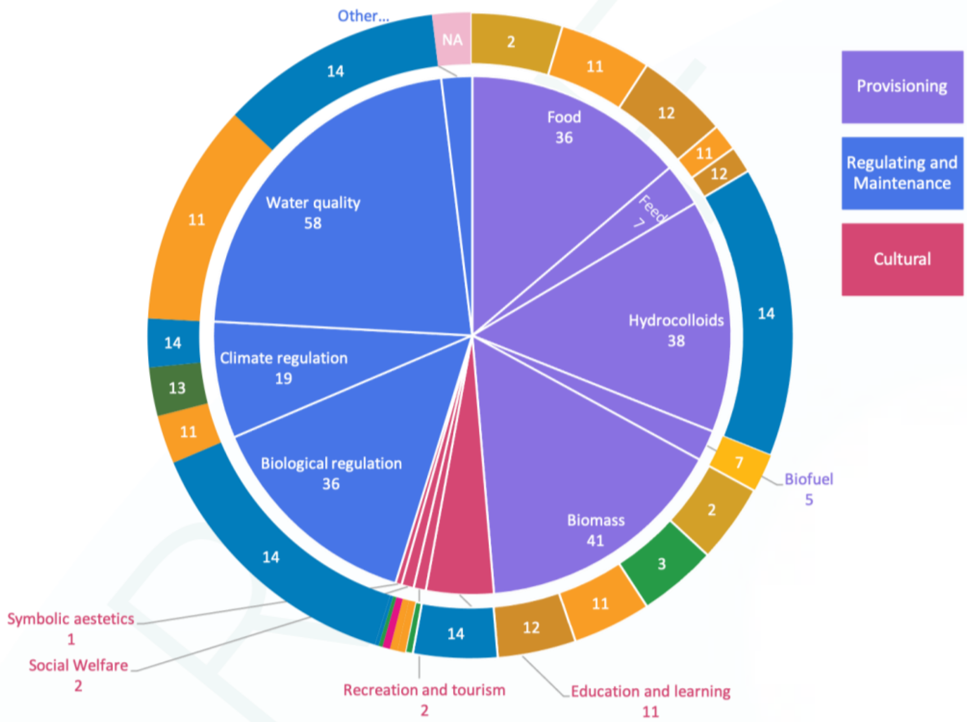

Fig.19 Relationship between each type of ecosystem service provided by seaweed cultivation (inner pie chart) and the related United Nations Sustainable Development Goals (UNSDGs; UN 2015; outer doughnut. The inner pie chart shows the number of studies from the QSR that showed evidence that the named ecosystem service is provided by seaweed cultivation. The ecosystem services are colour-coded according to the CICES classification (Provisioning, Regulating and Maintenance or Culture Services). The outer doughnut shows the UNSDGs that are addressed by the associated ecosystem services provided by seaweed cultivation. The UNSDGs are colour-coded according to the original UNSDG logo and the goal numbers are shown, except in cases where the doughnut slice is too small (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).

5.2.3. CONSTRAINTS

Within the analysed 280 studies, 143 (51%) studies identified a large number of constraints, which were classified within the different PESTEL categories related to seaweed culture. In addition, a further group ('Study') was identified to classify papers (35, equivalent to 12.4%) presenting constraints and weaknesses in their study design, such as limited length and scale of experiments/investigations and/or limitations in the modelling/statistical approach adopted (**Annex 3**).

Main Constraints. As shown in **Fig.20**, the key groups of constraint identified in the studies were environmental (40.4%) and technical (34.9%), followed by constraints in the economic, social and political spheres. These different subcategories will be analysed in more detail below.

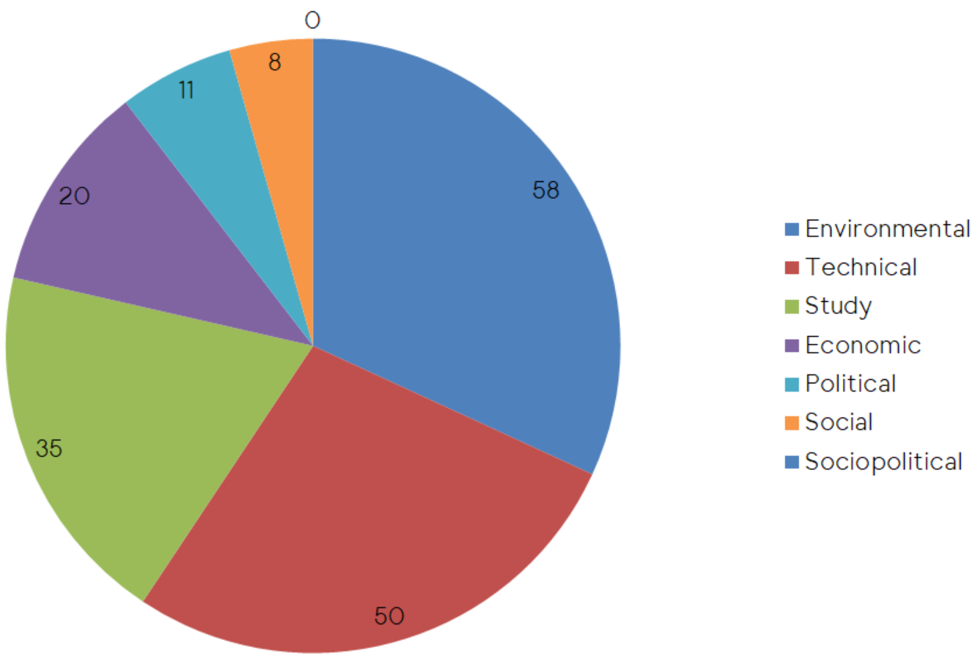

Fig.20 Classification of papers by **constraint categories** as described in **Annex 3**

Environmental constraints (Fig.21). Within the environmental constraints, **nuisance species** were the most dominant group **(27.6%)**, comprising organisms, growing either epiphytic on the fronds of cultivated species (e.g. 191, 129) decreasing their value (e.g. by encrustations); or attached on cultivation structures, forming blooms under favourable conditions, competing for light and nutrients (e.g. 55). This subgroup includes studies on associated planktonic microalgae (e.g. 31) as well as studies on different pathogens causing diseases (e.g. ice-ice disease) strongly affecting the harvest quality and quantity (e.g. 18). As second important environmental constraints **water conditions (24.1%)** were identified, in which elevated nutrient concentrations play a crucial role in increasing algal growth (e.g. 277, 258), whereas sewage from cities may also contribute pollutants, which can negatively affect quality and production in seaweed farms (e.g. 275). Consequently, ambient water quality is a crucial criterion for seaweed farm site selection (e.g. 29, 210). As third identified constraint **seasonality (17.2%)** is listed, due to the importance of different seasonal driven changes (e.g. water temperature, light, nutrient availability), affecting the growth and chemistry of cultivated macroalgae (e.g. 65, 230). Whereas next to abiotic also changes in biotic factors strongly interact with the growing bioresource, e.g. seasonal phytoplankton blooms (e.g. 255, 99). In addition, the presence of seaweed stocks affects the local fauna, which finds a temporarily limited shelter and habitat in the farms (e.g. 249, 92). Further information on the other subgroups can be found in **Annex 3**.

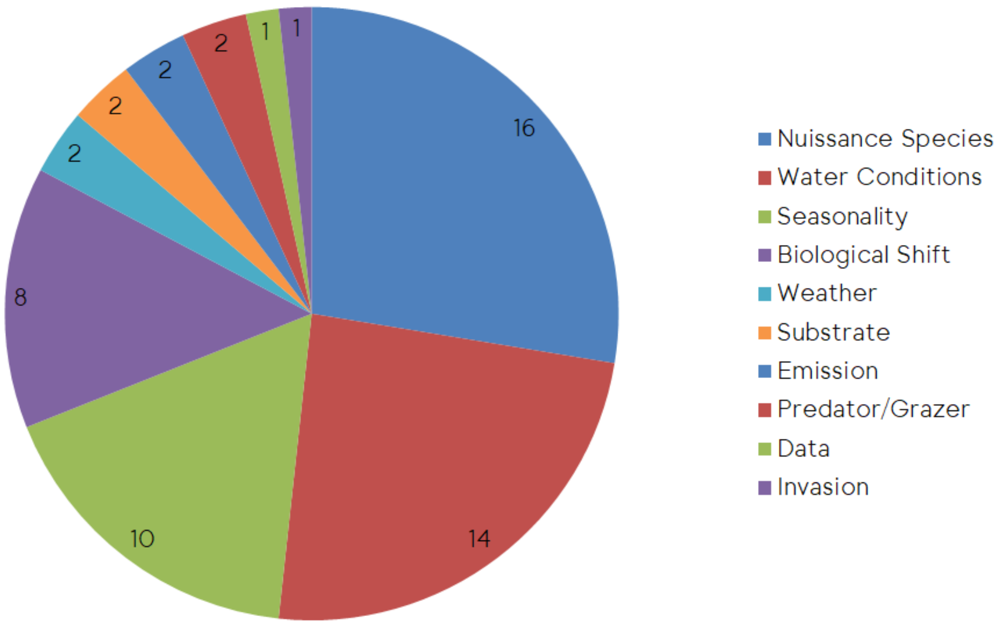

Fig.21 Overview of different **environmental constraints** as described in **Annex 3**

Technical constraints (Fig.22). 'Technology' and **'Production'** combined accounted for approximately half of the technical constraints identified (**28% and 24%** respectively). Examples of 'Technology' constraints include difficulties in implementing artificial upwelling to provide nutrients to seaweed farms (e.g. 57) and seaweed production at large scale (e.g 58); need of developments in the production of low carbon seaweed ethanol (e.g. 109) and mechanisation of farming (e.g. 175). Technical constraints relevant to 'Production' included nitrate uptake and inhibition in seaweed (e.g. 200), investigations on the potential nutrient bio-mitigation capacity of seaweed farms, also in IMTA contexts (e.g. 112, 243). Constraints around technical aspects at the **nursery** stage were identified in **16%** of the papers considered; these included strain selection (e.g. 185), intraspecific crossing between seaweed species (e.g. 276), nutrient uptake in tanks prior deployment of seaweed at sea (e.g. 87). Technical constraints in the context of **product quality** and **post-harvest** procedures and infrastructures were reported in approximately **10%** of the papers each. Brief description of the other subcategories can be found in **Annex 3**.

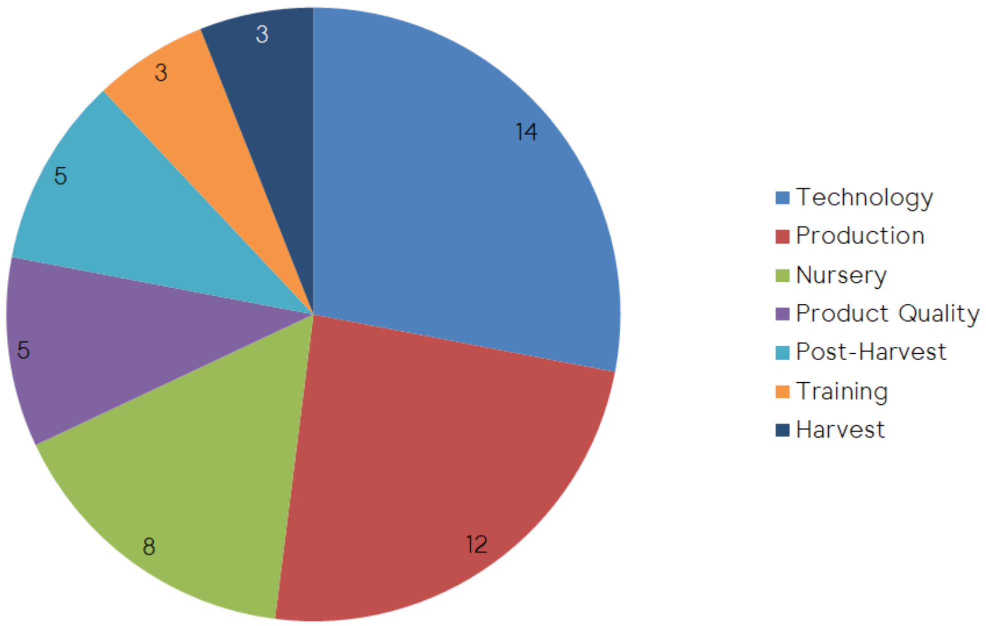

Fig.22 Overview of different **technical constraints** as described in **Annex 3**

5.2.4. NEGATIVE IMPACTS/RISKS

The majority (212) of the papers reviewed did not identify negative impacts or risks (**Fig.23**).

Among those that did report negative impacts or risks, environmental impacts were of the highest concern. Examples of potential environmental impacts of seaweed aquaculture included unknown impacts on deep sea communities, impacts on benthic communities, particularly seagrass beds (however, this was mostly relevant in tropical regions and not in Europe) and competition for nutrients with pelagic ecosystems. Of second highest concern identified was the potential of seaweed aquaculture to create large-scale macroalgal blooms, as has been demonstrated by *Ulva* blooms in the Yellow Sea due to *Pyropia* cultivation. However, all papers reporting the risk of macroalgal blooms resulting from seaweed cultivation were related to the regional events that have occurred in the Yellow Sea, and to date we could find no evidence of macroalgal blooms occurring due to seaweed cultivation in Europe. Additional negative impacts identified in the reviewed papers included introduced species, disease or pest outbreak, biofouling, light attenuation, conflict with other users (e.g. wind parks), increased halocarbon production (in tropical regions), flow reduction due to seaweed farms, changes in organic matter in surface sediments, and decreased benthic diversity. Finally, negative impacts that were placed in the "other" category were mentioned less than three times among the reviewed papers or they could not be assigned to a meaningful category. These included the following: poor acceptance of seaweed aquaculture among stakeholders due to bad experiences in other aquaculture sectors, creation of urban artificial shorelines, provision of jobs, but at the expense of farmers' health, competition with microalgae, ammonia release from seaweeds, competition with microalgae, and sediment deposition in beach areas. Nevertheless, many of these negative impacts were potential, and only very few papers provided clear, documented evidence of direct negative impacts of seaweed aquaculture.

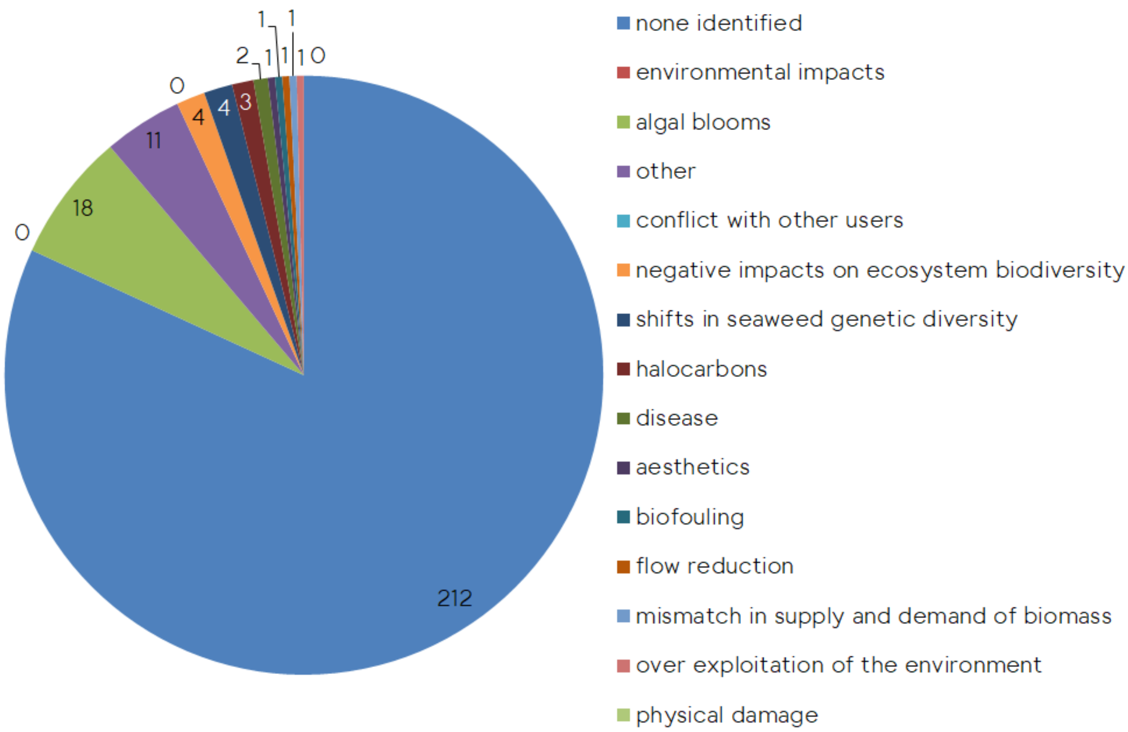

Fig.23 Overview of different **negative impacts** identified in QSR

5.2.5. KNOWLEDGE GAPS

From the 280 studies analysed, 172 (61 %) of the studies identified knowledge gaps. These gaps were classified into seven categories relating to seaweed culture using the PESTEL framework. In addition, a further category, not applicable ('NA'), was included, when no knowledge gaps were highlighted by the study (128 papers, equivalent to 45.7%) (**Fig.24**). The seven categories were further divided into 32 sub-categories and a full description of the knowledge gaps identified under each group/ sub-group can be found in **Annex 4**.

The main categories for knowledge gaps (other than NA) with the highest percentage were identified as Technical (24.5 %) and Environmental (18.7 %), followed by the social, economic and legal categories (**Fig.24**). It should be recognized that the low number of knowledge gaps in the social category might be a reflection of the lack of studies on cultural ecosystem services provided by seaweed cultivation (see **Fig.14**).

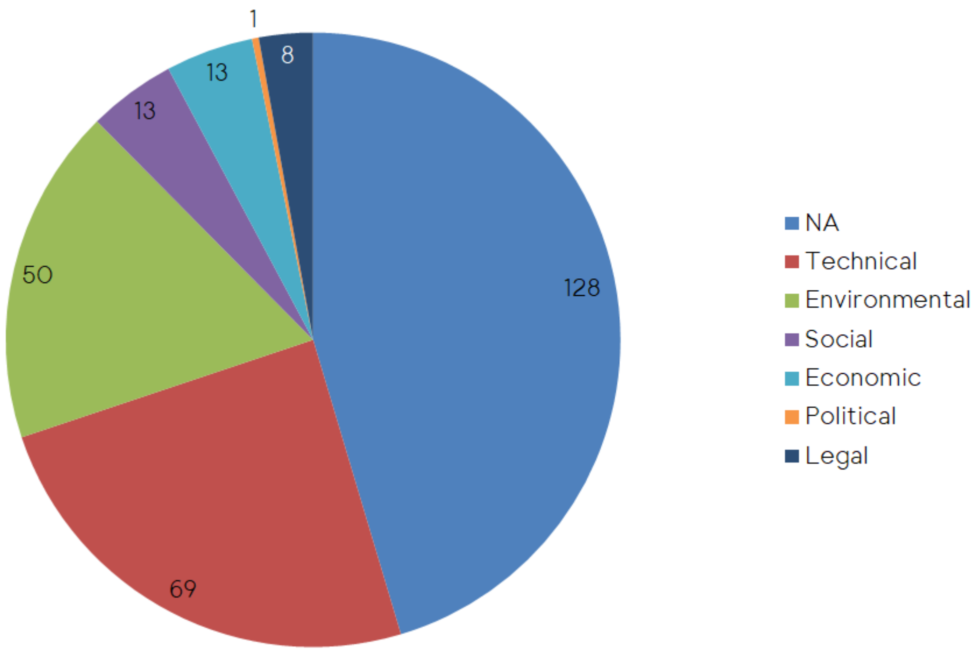

Fig.24 Overview of the key **knowledge gaps** identified through the Quick Scoping Review and classified into the eight main categories (n=280)

Technical knowledge gaps. Within the technical knowledge gaps, the production sub-category was by far the most dominant (47%), including how to accurately predict optimal farm size, production biomass and associated growth rates, particularly when using new farming methods (e.g., rafts) and/ or offshore locations (**Fig.25**). In addition, technical knowledge was highlighted as lacking in seaweed attachment mechanisms, the influence of depth, light exposure and aeration / water movement, in the nursery and on-growing phases, on growth rates and factors that influence/ limit nitrate and phosphate uptake at farm, regional and global scales. Also, the potential to monitor carrageenan content, disease outbreaks using satellites and biofiltration rates was also identified as a knowledge gap. The second most cited technical knowledge gap was identified as technology (23.5%), in which knowledge on the effectiveness of new innovative techniques at large scale, such as land/sea based IMTA systems, new seeding techniques, new species, floating longlines was identified. Knowledge gaps were also highlighted in energy saving processing (e.g., by-product extraction), effectiveness of depth-cycling to increase nutrient availability and prevent thermal stress and bioprospecting. The third most commonly cited knowledge gap was technology - unclassified (10.3%), in which the specific nature of the knowledge gap was not described. Further information on the other technical sub-categories can be found in **Fig.24** and **Annex 4**.

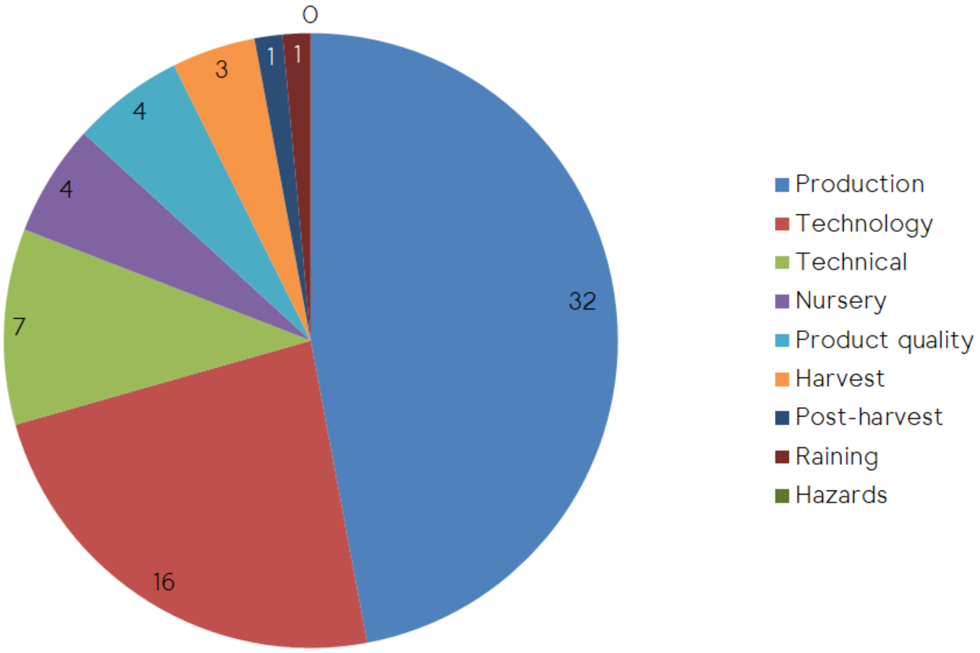

Fig.25 Overview of the **'Technical' sub-categories of knowledge gaps** identified through the Quick Scoping Review (n=68)

Environmental knowledge gaps. Within the environmental knowledge gaps, wider ecosystem effects were the most dominant sub-category (29.4%), comprising the gaps in knowledge of how upscaling seaweed farms would affect adjacent coral reefs, phytoplankton and microbial communities, seagrass beds, fish assemblages, fish farms, water quality, particularly in light of the creation of novel habitats. The lack of knowledge on the effect of stocking density on the wider ecosystem and the persistence of existing ecosystem services around the cultivation site, once in operation, were also highlighted (**Fig.26**). The second most cited environmental knowledge gap was identified as nuisance species/ disease (25.5%), in which how to deal with encrusting or epiphytic organisms, which can affect biomass, quality and/or cultivation process were highlighted. A lack of knowledge on seaweed diseases, biofouling, harmful algal bloom formation and their mitigation measures was also identified. The third most commonly cited knowledge gap was emissions and absorption (17.6%), in terms of absorption of CO2, uptake of nutrients and release of dissolved and particulate nitrates and phosphates from large-scale seaweed farms. In addition, lack of knowledge on what the benthic and carbon footprint of these large farms would be and how this would vary dependent on the species that was being cultivated was highlighted. Further information on the other sub-categories can be found in **Fig.26** and **Annex 4**.

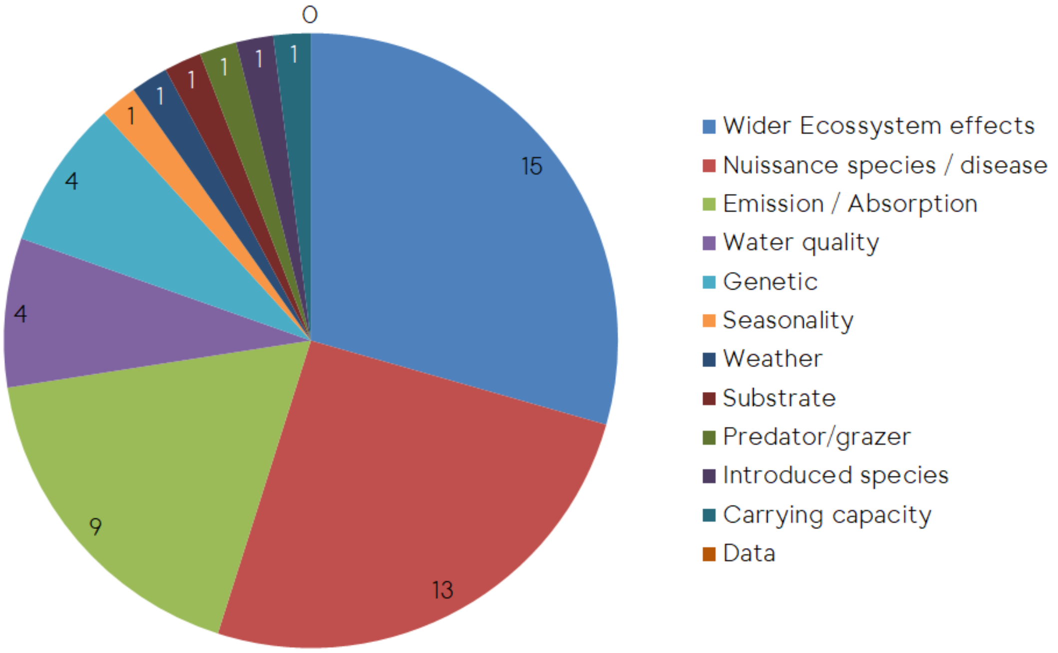

Fig.26 Overview of the **'Environmental' sub-categories of knowledge gaps** identified through the Quick Scoping Review (n=51)

6. DISCUSSION

6.1. REFLECTION ON THE METHODOLOGY

Assessing the replies to the first and second round of the Delphi questionnaire, the following observations are made. In reply to the questions, various respondents provided a few key words, not elaborating further. Given the expertise of the working group, these answers have been processed for further analysis. However, cautious of over interpretation, the answers were not reformulated. This shows, for example, in the section on knowledge gaps where answers provided were generally not formulated as a gap. The 22 answers obtained for the first round were considered satisfactory, even though they represented less than 20% of requests sent. The limited number of replies to the second round of the Delphi questionnaire is considered much more limited in terms of opportunities for analysis.

In general, we received a low number of expert opinions from the questionnaire used in the Delphi process. Most of the responses were from academia and research. Very few experts were from industry, NGOs, professional and international organisations. Additionally, few experts focused on marketing and sales, macroalgae genetic characterization and breeding, education, management and conservation of brown algae, kelp forest studies/seaweed diversity/phylogeography, and macroalgae diversity/macroalgae genetics/macroalgae horticulture. These observations suggest that in order to obtain a broader response, the different stakeholders may need to be engaged in different ways. Considering that it can be difficult to define ecosystem services and assess which of these are realistically provided by seaweed cultivation it is possible that some of the participants may have not been familiar with the concept of ecosystem services and how to define them. In the future, it will be necessary to take a more interdisciplinary and multi-stakeholder approach in order to reach a broader audience. Additionally, for future studies it would be important to increase the number of invitations and/or try to contact the potential respondents first, making sure they commit to be involved throughout the entire process.

6.2. QUALITY OF THE COMPILED DATA SET

Findings of the QSR strongly reflected that most of the studies were focused on pilot or small-scale farms, near-shore sheltered seaweed cultivation, mainly conducted in Asian and European countries. This underlies the novelty of seaweed farms in European waters, with no or limited examples of larger scale cultivation compared to other parts of the world where seaweed farms already operate at medium-large scales. It should be pointed out that there was a mismatch between the high scientific interest in seaweed cultivation in Europe (24% of scientific publications, ranked 2nd after Asia according to our QSR) and the low volume of seaweed production in Europe (<0.1% of total seaweed production; FAO 2019), compared to global production. The small size of seaweed farms (pilot and small farms 38% of studies vs. medium and large farms 26%) considered in most of the scientific studies might lead to some bias that needs to be considered when interpreting the results and identifying knowledge gaps, as some processes and services can be size dependent.

While assessing the papers, the expert working group identified weaknesses in experimental design or approach, analysis, and scale (both spatial and temporal), which affected about 12% of the reviewed literature.

The provided data set of QSR revealed a high diversity of seaweed taxa (about 77 species) approached in cultivation, whereas only few species, mainly belonging to the kelps, were the subject of intensive study and thus baseline of the present QSR. This might bias the outcome and conclusions in some way, considering that a variety of additional species/genera are identified and are currently tested for implementation in seaweed aquaculture. Also the approach of polyculture, e.g. IMTA combining the cultivation of different taxa at the same location, could alter the received findings in future.

Although European studies dealt with 17 different species, most of the studies were focused on kelps (*Saccharina latissima*, *Laminaria digitata* and *Alaria esculenta*) due to their present commercial value.

It must be also noted that there will probably be a time lag between the ongoing research and the results already published, as the former may not be represented in the QSR. On the other hand, as a result of the economical profitability of new applications and the patents limitations, these studies may be underrepresented in the published scientific literature.

6.3. ECOSYSTEM SERVICES PROVIDED BY SEAWEED CULTIVATION

While 85% of the ecosystem services provided by seaweed cultivation based on the Delphi process fell into the "Regulating and Maintenance" category, the QSR results showed 45% of studies provided evidence of "Regulating and Maintenance" services and 48.5% provided evidence of "Provisioning" services. However, in the second round of the Delphi process, when participants were asked to rank the ecosystem services in order of importance, provisioning services (e.g. food and hydrocolloids) were ranked as the most important ecosystem services. Although the ranking of the experts was not necessarily reflected in the literature, both methods identified the following top six ecosystem services provided by seaweed cultivation:

1) Provisioning food,
2) provisioning hydrocolloids and feed,
3) regulating water quality,
4) provisioning habitats,
5) provisioning of nurseries and
6) regulating climate.

6.4. KNOWLEDGE GAPS INHIBITING SCALE-UP AND DELIVERY OF ECOSYSTEM SERVICES BY MACROALGAE CULTIVATION

Diverse 'Technological' knowledge gaps were identified by both methods at all scales of the macroalgae cultivation process, from nurseries (e.g. strain selection, attachment effectiveness) to production and scale-up (e.g. biofiltration rates, ensuring consistent biomass/product quality, effectiveness of new technologies at scale) to processing (e.g. how to improve energy efficiency). This focus on technological knowledge gaps may result from the fact that the majority of the respondents to the Delphi questionnaire were from Europe, who generally may have less experience with seaweed cultivation at large scales.

The second most common category of knowledge gaps according to the Delphi process was 'Economic' (e.g. detailed market information/data, valorization of ecosystem services, carbon credits, and lack of successful business cases). In contrast, the second most common knowledge gap category identified during the QSR was 'Environmental' (e.g. wider ecosystem effects, nuisance species/disease, and emissions/absorption). The discrepancy in most commonly identified knowledge gaps between the two methods may be due to the fact that the economic knowledge gaps in the seaweed industry are often not reflected or reported in the scientific literature (e.g. business cases, yield costs may not be shared to protect industrial interests).

Based on suggestions from the expert respondents in the Delphi process, there is a clear need for a European-wide strategy for reducing risk for seaweed producers, providing clear standards and guidelines for obtaining permits, and providing financial support to improve technological innovation that will ensure consistent quality. Furthermore, it should be noted that seaweed biomass has generally a low gross monetary value and the labour conditions associated with seaweed aquaculture to be profitable are in many cases not acceptable for the European standards and legislation. In this sense, it would be critical for the development of European seaweed aquaculture to identify high-value products and technological innovations to reduce costs in terms of work hours.

An additional knowledge gap that was identified when analysing the ecosystem services provided by different taxa is that it needs to be determined if polyculture of macroalgae (using several algal species) will provide more ecosystem services than monoculture at a large scale.

Despite the fact that many experts ranked climate regulation as an ecosystem service provided by macroalgae cultivation, strong evidence of this service is still lacking in the literature and there are still many open questions regarding if and how macroalgae cultivation at a large scale can sequester carbon, and the carbon balance along the production chain.

6.5. MAIN CONSTRAINTS LIMITING SCALE-UP OF MACROALGAE CULTIVATION

The observed discrepancies between the constraints identified during the Delphi process (mainly Political/Legal, Technological, Economic) and the QSR (mainly Environmental and Technological), might be partly explained, as mentioned above for the knowledge gaps, by the novel/developing status of the seaweed aquaculture in European waters thus it shows a prioritised need for developing a required political/legal framework and establishing appropriate farming technologies. In addition, the high cost of labour in Europe compared to other countries where seaweed cultivation is well established requires a different approach, for example by incorporating technological advances that automate and, hence, reduce the cost of, seaweed production. Concerning the environmental constraints, the occurrence of nuisance species was the most dominant factor. This constraint is also reflected in the high number of papers that reported the occurrence of *Ulva* spp. blooms resulting from *Pyropia* sp. cultivation in the Yellow Sea as a negative impact of seaweed cultivation. Additional environmental constraints included site specific inter-environmental dynamics (e.g. seasonal appearance of nuisance species, alterations in water quality, pollution). Depending on regional water quality standards, some areas of Europe may be unsuitable for seaweed cultivation due to pollution. There are also seasonal restrictions in Europe that are not necessarily relevant in other regions where large-scale seaweed cultivation is already well established and can be carried out all year round. These seasonal restrictions limit the production period of some species, the ecosystem services that they can provide are not always present and hence the profit obtained. This reflects on the one hand the need for further investigation to understand the different abiotic and biotic factors involved and also underlines the required flexibility concerning site specific adaptations for establishing a working seaweed farm. In this context, accompanying monitoring could be a way to provide further support for the planning of new and further implementation of already established sites.

6.6. POTENTIAL NEGATIVE IMPACTS OR TRADE-OFFS OF SCALING-UP MACROALGAL CULTIVATION

Unknown environmental impacts to deep sea, benthic and pelagic ecosystems was one of the most commonly identified potential negative impacts of macroalgae cultivation both among the expert responses and the reviewed articles. This point is especially relevant if the goal is climate change mitigation due to the scale required and the large amount of biomass that could be entered in the deep ocean.

In addition, conflicts with other users, shifts in seaweed genetic diversity, negative impacts on ecosystem biodiversity and reductions in water flow were identified as potential negative impacts of scaling-up macroalgae cultivation by both methods. Nevertheless, most negative impacts were identified as potential or unknown and few studies provided direct evidence of negative impacts of seaweed cultivation, except in cases of poor management practice (e.g. cloning, uncontrolled transport of strains between sites/regions). This underlines again the need of further, accompanying multidisciplinary approaches and transparency, considering site specific conditions and need for comparative examples. In this context the built and interlinking of interdisciplinary seaweed farmer- research networks, providing information and access to developing methodologies, as well as information on successful case studies, would provide a sustainable way to support the further developments in the seaweed cultivation sector.

7. CONCLUSIONS

The present study highlights that seaweed cultivation can provide many ES to humanity. However, one of the main issues recognized during the presented study was the understanding of ES themselves by the different stakeholders. There was often no clear evidence of ES provided found in the literature and also some aspects, like cultural impact etc. were missing in the responses to the questionnaires during Delphi process. At present, there seems to be not only uncertainties in definitions, but also a lack in understanding of the potential importance of the defined ES for further development of the seaweed cultivation industry. Clear definitions of ecosystem services are required to be communicated and agreed within and among stakeholders involved in seaweed cultivation to facilitate further valorisation and analysis of ecological and economical footprint of large-scale seaweed production. In this context the presented approach combining CICES v.5 and PESTEL analysis provided a valuable tool to define and categorise ES in the seaweed cultivation sector.

Most of the studies addressing ES provided by seaweed aquaculture were not comprehensive and overall focused on a few services (e.g. biomass provision, nutrient removal, biological regulation or blue carbon), while others (e.g. cultural services) were poorly represented. However, the number of studies reporting a certain service (e.g. regulating water quality) is not necessarily a direct reflection of the importance or value of that particular service. There is clearly a bias in the literature on studies investigating bioremediation of seaweeds, but very few studies provide valorisation of this service. In contrast, cultural services such as improving social welfare or gender equality are poorly represented in the literature. That is not to say that such cultural services are less valuable than water quality regulation, but such a direct comparison of the value of different ecosystem services provided by seaweed cultivation is still lacking, as it was outside the scope of this study.

Relevant knowledge gaps have been identified in most of the PESTEL categories, particularly in technological, economical/social and environmental issues. Technological improvements, and the identification of valuable products and species were the main actions suggested by experts during the Delphi process in order to harness the potential of seaweed aquaculture in Europe. The lack of a clear legislation about biomass quality standards (e.g. content of heavy metals, contamination by bacteria and other compounds of potential concern for human health) and guidelines to obtain the necessary permits is another problem usually highlighted by seaweed farmers constraining the development of seaweed cultivation. In addition, only limited information about the potential consequences of climate change for macroalgae cultivation has been reported so far. Even in these cases, the scale of aquaculture facilities was generally limited and currently there is an important uncertainty about the upscaling of the activity. It should be noted that climate and environmental conditions, and the viability of seaweed aquaculture and its provision of ES could be interrelated when seaweed aquaculture is developed at a large scale. For instance, in some regions where seaweed aquaculture has been developed at large scale, the fertilisation of coastal waters has been necessary to increase or maintain the production of seaweeds. This raises the need to control the nutrient fluxes connected with large-scale seaweed cultivation. Although there is a relevant number of studies dealing with nutrient (including carbon) removal and bioremediation, most of the studies did not consider the entire life cycle, and overall did not discuss the scale of the facilities or cultures necessary for an effective remediation.

Several of the ES will be delivered only at large scale cultivation (e.g. carbon sequestration, climate regulation). At this scale of operations there could be multiple associated unknown side effects which need to be further investigated (e.g. pumping deep waters to fertilise seaweed which not only bring to the surface required growth-limiting nutrients, but also already sequestered carbon). .

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ANNEX 1: WORK DOCUMENT OF THE DELPHI PROCESS

QUESTIONS SENT TO THE EXPERTS FOR THE FIRST ROUND OF THE DELPHI PROCESS

Dear Expert,

RE: Expert opinion requested to highlight knowledge gaps for enabling the upscaling macroalgal cultivation in European waters

This questionnaire is part of ongoing work carried out under the framework of the EKLIPSE Macroalgae expert group. This group was formed in February 2021 as a response to a request made to Eklipse by the European Commission's Directorate General for Maritime Affairs & Fisheries, Unit for Maritime Innovation, Marine Knowledge and Investment (DG MARE), following Eklipse's fifth call for requests (CfR.5/2020). The request was: What are the knowledge gaps to be addressed before harvesting the potential of macroalgae culture in providing climate-related and other ecosystem services (i.e., coastal protection; nutrient recycling; lower impact food; lower impact material; etc.) especially at larger scales?

For the purpose of this work, we consider the definition of Ecosystem Services as accepted by CICES (available from www.cices.eu).

With a strong focus on the identification of knowledge gaps on ecosystem services and macro-algae cultivation, this Eklipse exercise will take into account qualitative and quantitative data. Such assessment is needed to critically assess the potential of upscaling macroalgae culture to serve as a solution to mitigate climate change, enhance coastal biodiversity and provide sustainable ecosystem services. Eklipse results are expected to inform future macroalgae research and Commission activities, through the identification of knowledge gaps.

You are receiving this information because you were selected as an expert and/or key stakeholder and we value your opinions on this matter. We kindly ask you to reply to the questions below within 7 days. There is no word limit for your replies, but we do ask you to be as specific as possible. There is no need to elaborate your answers with justifications (such as references). We estimate that the questionnaire will take no longer than 20 minutes to complete.

Please note that this is the first round of questions for this Delphi process and we will be very grateful if you would be happy for us to contact you again in a few weeks for further rounds. These next rounds may, for instance, ask you to rank the answers given during the first round and secondly ask you to review your initial ranking based on the overall responses provided.

To standardize the language of marine aquaculture, we propose three site categories: "nearshore sheltered", "nearshore exposed" and "offshore" sites, according to Bak et al. (2020). These categories are dependent on two site attributes: "water depth" and "distance to shore". The offshore site category is reserved for sites with a distance to shore of ≥3 NM; the nearshore exposed are sites with a water depth ≥50 m yet <3 NM from shore; finally, the nearshore sheltered sites are those with a water depth <50 m and <3 NM from shore.

For the following questions please specify whether your answers are applicable to land based cultivation, transitional (e.g., estuaries) or marine waters (e.g., near shore sheltered, near shore exposed, off shore) or common to some or all of these.

1 – Please list the most important Ecosystem Goods and Services (ES) that macroalgae cultivation can provide.

2 - What are the knowledge gaps on macroalgae cultivation (e.g., processing and marketing) that would need to be addressed in order to upscale it and enhance its delivery of ES?

3 – What are, in your opinion, the main constraints (e.g., technological, political, economic, legal, social, environmental) that need to be resolved before significantly upscaling macroalgae culture?

4 – What negative impacts or trade-offs may upscaling macro-algae cultivation lead to, particularly when it comes to ES?

Background assessment of the participants

1 – Which of the following sectors do you consider most relevant to your experience?

A) Academic/research
B) Industry (e.g., producer, processing, marketing and sales)
C) NGO (e.g., environmental)
D) Other marine organizations (e.g., political entities, professional associations, other not included elsewhere)

2 – If you belong to the Academic or Industry sector, on which aspect do you focus your work:

☐ Macroalgae hatchery/nursery
☐ Macroalgae cultivation
☐ Macroalgae processing
☐ Marketing and sales

3 – Is your work experience focused on one country or region? If yes, please specify.

☐ Asia and the Pacific:
☐ Europe:

☐ Latin America and the Caribbean:

☐ Near East:

☐ North America:

4 – Is your work experience particularly focused on a macroalgae species or group of species? If so, please specify.

5 – Is your work experience focused on a specific site category from the following: land-based cultivation, transitional (e.g., estuaries) or marine waters (near shore sheltered, near shore exposed, off shore)

Please choose your work area (click here)

6 – How many years of work experience do you consider yourself to have?

☐ 1 – 5 years ☐ 6-20 years ☐ more than 20 years

QUESTIONS SENT TO THE EXPERTS FOR THE SECOND ROUND OF THE DELPHI PROCESS.

Dear Expert,

RE: Expert opinion requested to highlight knowledge gaps for enabling the upscaling of macroalgal cultivation

First of all, we thank you once again for the time you spent in the previous round of this process. Your contributions are extremely important for our work group.

As explained in our previous message, as a follow up of the 1st round of the Delphi process, we now ask your contribution for the second and final round. In this stage we have only four tasks. Essentially you are asked to rank the 5 most important options listed, which are derived from all the answers obtained in the previous round.

1 – From the list of Ecosystem Goods and Services (ES) presented below, please select the 5 that are most important for you and rank them from 1 to 5, where 1 is the most important and 5 is the least important of the ones selected. This list was obtained from the answers in the previous round.

☐ Macroalgae grown for **food** (including hydrocolloids)

☐ Macroalgae grown for **feed**

☐ Macroalgae grown as a **source of energy**

☐ Regulation of **Water quality** (including eutrophication, biomitigation, bioremediation)

☐ **Carbon sequestration/storage/accumulation** by macroalgae

☐ **Climate regulation** (CO_2, carbon cycle, DMS, OTHER)

☐ **Coastal protection** (erosion, wave reduction, flood control)

☐ **Maintaining nursery populations and habitats** (including gene pool protection)

☐ **Pest and disease control**

☐ Characteristics of living systems that **enable education and training**

☐ Elements of living systems used for **recreation and tourism**

2 - From the list of knowledge gaps presented below, please select the 5 that are most important to you and rank them from 1 to 5 where 1 is the most important and 5 is the least important of the ones selected. If you include a category with subcategories please rank also those.

Note that these are the knowledge gaps on macroalgae cultivation that would need to be addressed in order to upscale it and enhance its ES, according to the answers from the previous round.

☐ Environmental Data

Occurrence/impact of nuisance species

Biodiversity impact

Nutrient uptake/bioremediation

☐ Farming Technologies

Ensure consistent production quality

Strain improvement

Technologies for further cultivation approaches

Develop mechanization for seaweed farming

☐ Technologies for macroalgae processing

☐ Data obtained from “real” macroalgae farming

Appropriate scale of production

Appropriate spatial planning for farming sites

☐ Market data

Adequate price

Adequate value-chain connections

Detailed market information

☐ Economic data

Information on valorization of Ecosystem Services

Appropriate business cases

☐ Politics

☐ Certification

Food Safety

CO_2 footprint

Ecosystem provisioning

☐ Training

2.1 Please provide, in a concise manner, possible ways (tasks and/or key players) to address those knowledge gaps.

“SPACE FOR TEXT”

3 – From the list of negative impacts or trade-offs that macroalgae cultivation upscaling may lead to (identified in the previous round of questions) please select the 5 that you think are most severe and rank them from 1 to 5, where 1 is likely to be the most severe and 5 is the least severe of the ones selected.

☐ Conflict with other users/uses (at land or sea)

☐ Negative impacts on ecosystem biodiversity

☐ Aesthetics

☐ Mismatch in supply and demand of biomass

☐ Unknown environmental impacts (e.g. on deep sea, benthic and pelagic ecosystems)

☐ Over exploitation of the environment

☐ Shifts in seaweed genetic diversity

☐ Pollution (e.g. plastics)

☐ Water flow reduction

☐ Physical damage (e.g. damage to the sea floor resulting from the farming structures, anchors, stakes, etc.)

ANNEX 2. OVERVIEW OF DIFFERENT CATEGORIES USED FOR CLASSIFICATION OF DIFFERENT ARTICLES SELECTED IN THE QSR

N°	Category	Subcategories	Explanation
1	Species		Species or taxonomic group considered in the study.
2	Country		Country, countries or geographic region (e.g. North Atlantic coast of Europe) where the study was performed
3	Scale	NA/Local/Regional/ Large/Global	Specify study scale choosing one of the options
4	Sector	NA	
		All	Non specified or seaweed aquaculture in a general sense
		None	Seaweed harvesting, seaweed as resource…
		Land-based cultivation	Cultivation of macroalgae on land.
		Transitional	Cultivation of macroalgae in estuarine or brackish waters.
		Near-shore, sheltered	Cultivation of macroalgae in marine waters <50 m water depth & <3 NM distance to shore.
		Near-shore, exposed	Cultivation of macroalgae in marine waters >50 m depth & <3 NM from shore.
		Offshore	>3 NM from shore.
5	PESTEL analysis	NA	
		Political	
		Economic	
		Social	

		Technical	
		Environmental	
		Legal	
6	Aquaculture type	NA	
		All	Non specified or seaweed aquaculture in a general sense.
		None	Seaweed harvesting, seaweed as resource...
		Land-based cultivation	Cultivation of macroalgae on land.
		Transitional	Cultivation of macroalgae in estuarine or brackish waters.
		Near-shore, sheltered	Cultivation of macroalgae in marine waters <50 m water depth & <3 NM distance to shore.
		Near-shore, exposed	cultivation of macroalgae in marine waters >50 m depth & <3 NM from shore.
		Offshore	>3 NM from shore.
7	Study protocol	NA	NA
		BACI	Studies considering a "Before-After-Control-Impact" design.
		Before-After	Studies considering conditions previous to the installation of seaweed aquaculture facilities.
		Control-Impact	Studies comparing natural communities and seaweed crops.
		Descriptive	Descriptive or observational studies with no comparisons with references.

		Other	Other studies not considering quantitative or qualitative analyses.
		Modelling	Studies using models to assess or identify ecosystem services or disservices.
8	Farm size	N/A	not defined in the methodological part
		Pilot	Small-scale, experimental farm to test feasibility
		Small	e.g. family runned farms of villages
		Medium	e.g. larger farming activities but not as extended as covering bays, regions; or farms with < 50 lines (x 200 m; Campbell et al. 2019)
		Large	e.g. farming activities covering whole bays, regions, or large coastal areas; or farms with > 50 lines (x 200 m; Campbell et al. 2019)
9	Provisioning	NA	not defined in the methodological part
		Food	
		Hydrocolloids	
		Feed (specified)	
		Other (specified)	
10	Regulating and maintenance	NA	not defined in the methodological part
		Biological regulation (specified)	Alien species, biodiversity/genetic conservation, habitat provision, algal bloom regulation, other.
		Water quality	Eutrophication, biomitigation, bioremediation. Specified.
		Coastal protection	Erosion, wave reduction.
		Climate regulation (specified)	CO_2, carbon cycle, DMS, other.

		Other (specified)	
11	Cultural	NA	
		Symbolic and esthetic	
		Recreation and tourism	
		Cognitive (specified)	Inspiration
		Scientific knowledge (specified)	e.g. Number of proposals/grants.
		Education/learning	
		Other (specified)	
12	Knowledge gaps		
13	Identified constraints		
14	Disservice/Negative Impacts/Trade-Offs		
15	Disservice comments		
16	Expert notes		
17	Specified		Additional information to different drop-down points, when required

ANNEX 3. OVERVIEW OF DIFFERENT TYPES OF CONSTRAINTS IDENTIFIED IN THE ANALYSED LITERATURE.

PESTEL	Type	Description
Study	Length	Insufficient study length
	Size	Small scale (spatial and temporal) experiment
	Stats	Correlational data, not evaluated data
Environmental	Data	Insufficient amount of environmental data
	Seasonality	Seasonal effects, e.g. during growing harvesting period
	Weather	Storms and extreme events
	Substrate	Effect of type and conditions of natural or artificial substrate
	Emission	CO_2, Nutrients balance - footprint
	Nuisance species	Encrusting or epiphytic organisms affecting biomass quality or cultivation process; diseases
	Water conditions	Water quality and remediation processes and pollution load not sufficiently known
	Predator/grazer	Grazing on cultivated macroalgae
	Biological shift	Effects on taxa and communities adjacent to the seaweed farm
	Invasion	Introduction of invasive non-native species
Economical	Financiation	Unclear/unspecified financial viability, dependence on other lifestocks

	Market	Market and value chain elements
Technical	Nursery	Seedling, stock quality, new strains in cultivation
	Post-Harvest	Management and processes after harvesting
	Harvest	Timing, techniques etc. harvest-related
	Production	Amount of produced biomass, production speed
	Product quality	Quality of seaweed products
	Training	Training of people
	Technology	Development in technology
Political	ABS	Access benefit sharing
	Dependence	Close relation / connection to other activities, e.g. wind parks
	No support	No governance support
	Space	Use of space
	Awareness	Potential provision of ecosystem services
Social	Gender	Gender inequality observed
	Jobs	Jobs connected with seaweed aquaculture
	Stakeholder	Stakeholder perception

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2143 ## ANNEX 4. - OVERVIEW OF DIFFERENT TYPES OF KNOWLEDGE GAPS IDENTIFIED
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PESTEL	Type	Examples
Environmental	Data	Uncertainty associated with modelling, need for more validated models, need for systematic data collection
	Seasonality	Observed seasonal/ inter-annual effects, e.g. growing/ harvesting period
	Weather	Observed effects of more severe weather events e.g. storms
	Substrate	Effect of present natural or artificial substrate (type, conditions), creation of novel habitats
	Emission/Absorption	CO_2, Nutrients balance - food print, species dependent, Carbon footprint (using seaweed as terrestrial crop fertiliser), need for LCA for CO_2 regarding bioethanol production, impact of emission of volatile halocarbons
	Nuisance species / diseases	Incrusting or epiphytising organisms affecting biomass quality or cultivation process, diseases, biofouling, HAB formation and mitigation measures, influence of environmental conditions
	Water quality	Water quality and remediation processes and pollution load not sufficiently known, nutrient inputs from terrestrial systems, cultivation in transitional waters
	Predator/grazer	Grazing on cultivated macroalgae vs epiphyte control, effect of grazing on production losses
	Introduced species	Introduced species, population etc. spreading in comparison to local types, maintenance and biosecurity
	Wider ecosystem effects	Effect of farms on coral reefs, phytoplankton communities, seagrass beds, fish assemblages/ landings, fish farms, water quality, 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

	Genetic	Effect on native seagrass genetic diversity, relationship between native and wild populations, influence of geographical distance and habitat discontinuity
	Carrying capacity	Effect on carrying capacity of region
Economical	Financial	Financial viability, co-culture potential, sharing of ABS agreements
	LCA	Life Cycle Assessment for different products (e.g. biofuel, protein, liquid fertilisers) and culture environments (e.g. seawalls). Need to consider climate change in risk analysis
Technical	Nursery	Seedlings, reproductive life cycles, stock quality, new strains in cultivation, development of new strain markers, nutrient storage/ deficiencies on pre-deployment phase, optimal stocking densities in IMTA systems, new cultivars to improve nutrient uptake, role of microalgae unintentionally introduced into system. Optimisation of aeration regimes.
	Post-harvest	Management and processes after harvesting, e.g. way lengths, use of valuable pigments, biofuel production, downstream processing
	Hazards	In production process
	Harvest	Quality, timing, techniques etc. concerning the harvest, particularly when upscaling, stocking density
	Production	Amount of produced biomass, production speed, use of new farming methods (e.g. rafts) and associated growth rates, life cycle emissions, attachment mechanisms, influence of depth on growth rates, influences on nitrate/ phosphate uptake/ limitations, monitoring of carrageenan content using satellites, biofiltration potential, optimum light exposure. Effects of low water movement. need for longer experimental periods. Need for larger size of experiments (spatial and temporal), N/P global uptakes. Offshore farm design. Optimisation of aeration regimes (as in Nursery section).
	Product quality	Greater knowledge on carrageenan chemistry
	Training	Seed selection criteria

	Technology	New technology - effectiveness, use of land/ sea based IMTA systems, new seeding techniques testing, new species, floating longlines, potential of secondary organisms in process. Energy saving processing (by-product extraction), improving growth in low nutrient environments, effectiveness of depth-cycling to increase nutrient availability/ prevent thermal stress, bioprospecting
Political	ABS	Access benefit sharing
	Dependence	Close relation/ connection to other topics, e.g. wind parks
	Support	Need to develop policies to guide markets
Social	Gender	Gender inequality observed, need for support mechanisms for access to information, resources, services, input to shaping risk assessments
	Jobs	Jobs connected with SA, creation of jobs for fishing communities
	Stakeholder	Stakeholder perception, acceptability, development strategies, site selection, impacts on communities, communication and Knowledge transfer
	Occupational Health	Farmer safety - issues and solutions
	Coping with climate change	Adaptive strategies for seaweed farming communities to cope with climate change
Legal	Governance	Governance (e.g. co-location of seaweed farms with offshore wind), spatial planning, biosecurity, international framework for biosecurity required, need to establish rules on verification of air-sea CO2 flux and permanence of carbon storage, lack of policies specific to seaweeds (e.g. no list of specific diseases/ pathogens)
	Contaminant limits	Regulations on contaminant levels (e.g., bacteria)