



# Prospective seaweed systems for North-West European waters

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## Abstract

Seaweed is a potential source of sustainable food, feed, cosmetics, biomaterials, and biostimulants. Seaweed is currently mainly grown in Asia, and it is unclear which seaweed systems are best suited for North-West European waters. We use an expert workshop and a written feedback round to identify prospective seaweed systems, including the cultivation site and post-harvest stages, for three different contexts. Independent of the context, there is a preference for cultivating multiple species and having a high level of automation. Depending on the context, the optimal choice with regards to scale, substrate, seeding technique, and the integration of seaweed farming with (shell)fish species differs. Profitability of the systems, availability of (large-scale) processing facilities and ships to go offshore, uncertainty of buyers, and obstacles in seed stock availability, permits, and building infrastructures present key challenges and risks. The identified seaweed systems serve as input to the policy debate around alternative resource production in Europe and can help in developing standards for seaweed system design. Furthermore, researchers and technology providers can use the prospective systems for future profitability assessments and directions for technology developments.

**Keywords:** cultivation; post-harvest; kelp; sector development; sector vision; workshop

## Introduction

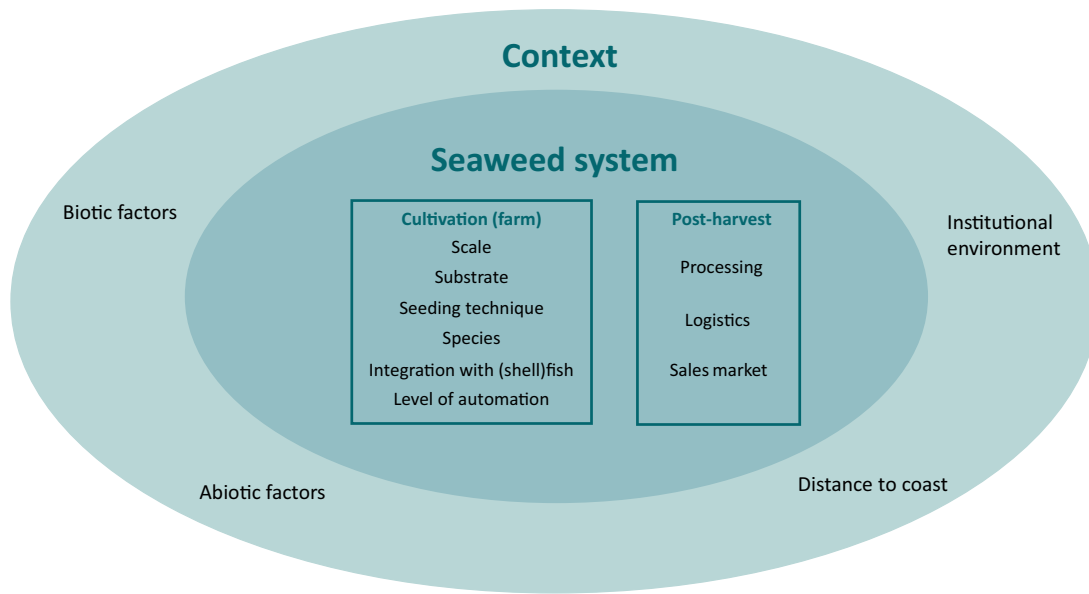
Seaweed is gaining increasing interest in Europe, as the demand for food and bio-based resources rises due to a growing global population and climate challenges (EC 2022). Seaweed excels as a useful resource for multiple applications and, in contrast to terrestrial production, does not require extensive use of land, fresh water, or fertilizer (Spillias et al. 2023). The European Commission recognizes the potential of algae, such as seaweed, as a source for sustainable food and feed (EC 2022).

Nevertheless, the scaling of the European seaweed cultivation sector faces challenges. First, uncertain profitability of seaweed cultivation in Europe currently hinders investments, adoption by farmers, and diffusion (van den Burg et al. 2016, Chaisemartin de et al. 2021). Compared to Asia, the high labour costs in Europe hamper price competitiveness (Tullberg et al. 2022). A second challenge is the availability of nearshore space, i.e. close to the coast, where seaweed farms compete for space with tourism, shipping, and fishing (Tullberg et al. 2022). These challenges illustrate the difficulty in choosing the right cultivation practices, as well as the supply chain design of seaweed systems in Europe, despite their potential benefits. We define seaweed systems as the cultivation site and post-harvest stage.

Prior research on the European seaweed sector focuses on economic competitiveness as well as technical possibilities and developments (Araújo et al. 2021). van den Burg et al. (2021)

conclude that the European sector could develop if it aimed to produce high-value products from seaweeds and that certification and labelling could distinguish European from Asian production. Farmers will also have to make smart choices regarding the location of the cultivation site, the level of mechanization, seeding technique, and logistics. Tullberg et al. (2022) propose to move the cultivation setup offshore and operate within a wind farm to reduce competition for space and share labour, transportation, and infrastructure to reduce costs. Jansen et al. (2023) investigate the potential of offshore aquaculture in the Dutch North Sea. They argue that mechanization may facilitate the scale-up of seaweed farms. In a Danish case study, Boderskov et al. (2021) analyse the effect of direct seeding on the yield and quality of *Saccharina latissima* (Phaeophyceae). Direct seeding is a novel seeding technique that requires less labour and forgoes an expensive hatchery phase, thereby reducing seeding costs (Boderskov et al. 2021).

Currently there are ~153 seaweed producers in Europe, of which most (68%) enterprises harvest seaweed from the wild (Vazquez Calderon and Sanchez Lopez 2022). Seaweed production with aquaculture is at an early stage of development in Europe, while this form of seaweed production is necessary to satisfy growing demand without the depletion of wild seaweed stock (Araújo et al. 2021). If we are to achieve the political target of a strong seaweed sector in the European Union (EC 2022), knowledge about prospective seaweed systems is essential.



**Figure 1.** Conceptual framework to identify prospective seaweed systems.

Despite these important contributions and developments, there is no comprehensive view on prospective seaweed systems in Europe. We define a seaweed system as cultivation site and post-harvest stage. We aim to identify prospective seaweed systems for North-West European waters. Via an expert workshop and written feedback round, we identify seaweed systems that consider the technical state of the art in seaweed cultivation as well as the operational context. We further analyse risks and challenges of these systems. We focus on kelps, brown macroalgae that are commonly considered most suited for large-scale cultivation in Europe (Kerrison *et al.* 2015, Araújo *et al.* 2021). Our study area of North-West European waters represents a large cultivation area with different geographical characteristics for which experts are available.

We engaged sector experts, i.e. seaweed researchers, farmers, and supply chain actors, to identify optimal decisions for the three different contexts at the cultivation level, e.g. on scale or seeding technique. The three contexts are: (i) nearshore, (ii) offshore single enterprise, and (iii) offshore in a wind farm. The obtained insights are valuable for different stakeholders. First, technology developers can use our results to prioritize their research and development efforts. Second, farmers may rely on our results to inform farm (re)design decisions. Third, financial institutions can use our findings to create economic benchmarks for seaweed farms to assess the financial risks for similar seaweed systems before supplying a loan. Fourth, our results can guide standardization institutes in defining seaweed farm design standards for the different identified seaweed systems. Fifth, the findings can inform policy debates on targeted support to the sector by proving a classification of different seaweed systems, which can nuance the policy debate and stimulate solutions to current challenges, risks, and obstacles for the seaweed systems.

We present our conceptual framework in the next section. The third section describes the methodology, i.e. the expert workshop and the written feedback round. The fourth section presents the results and visualizes the three prospective

seaweed systems. We discuss the implications of these systems and present our conclusions in the fifth and sixth sections.

## Conceptual framework

Our conceptual framework has two main parts: (i) the seaweed system and (ii) its context (Fig. 1). This framework outlines the key parts of the seaweed system, consisting of the cultivation stage (the farm) and the post-harvest stage. Based on the context, farmers need to design the optimal seaweed system by making choices on the cultivation and post-harvest stages.

The optimal decisions for farmers and value chain actors regarding the cultivation and post-harvest stages of seaweed systems are determined by the context (Fig. 1). The context includes biotic factors (e.g. pathogens, biodiversity, or herbivores), abiotic factors (e.g. salinity, water temperature, or water depth), distance to the coast, and the institutional environment (e.g. regulations, conventions, or established markets). The seaweed system itself includes cultivation (scale, substrate, seeding technique, species, integration with (shell)fish species, and level of automation) and post-harvest stages (processing, logistics, and sales market).

### Cultivation variables

The scale of a seaweed farm has implications on the yield, production costs, and environmental impact. While large-scale operations may yield more output, they may also cause a greater negative environmental impact (Campbell *et al.* 2019), and require substantial financial investments (Emblemsvåg *et al.* 2020). Nevertheless, economies of scale in large-scale farms may result in cost efficiency by having a decreasing average cost per kg yield as the farm size increases (Duffy 2009). Price reductions on a large scale can occur by spreading fixed costs like machines and ships over a larger amount of yield, while also discounts for larger amounts of seeding material and substrate are expected (Duffy 2009). The substrate, which we define as the structure to which the seaweed is attached

and on which it grows, can take different forms (Boderskov et al. 2023, Wieling and Wieling 2023). These forms include long lines, multiple lines, and nets, while the success of each form depends on the context of the seaweed system (Boderskov et al. 2023). Deployment of a net system or a multiple-line cultivation system increases the line density, increasing the yield per square meter of sea surface (Boderskov et al. 2023). The success of cultivating on nets could depend on the water conditions such as the depth and turbidity of the cultivation site (Azevedo et al. 2019, Boderskov et al. 2023). Azevedo et al. (2019) found that the light extinction coefficient in the water decreased with increasing depth, leading to decreased growth. Furthermore, Boderskov et al. (2023) found lower biomass yield on the deeper lines, which they argue is due to turbidity and self-shading. These findings indicate that the amount of light available at the lower parts of the net affects the success of net cultivation. The population density, the number of individuals per m<sup>2</sup>, can next to the choice of substrate also be influenced by the amount of seeding material a farmer puts on the substrate (Sato et al. 2023). It is important that the appropriate population densities are selected to optimize biomass yield and quality of the kelp (Kerrison et al. 2017, Sato et al. 2023). Farmers must also decide which seeding technique to use: twine seeding or direct seeding. Twine seeding involves growing juveniles on a twine in a hatchery before transferring them to a farm site (Kerrison et al. 2020). In the case of direct seeding, juvenile sporophytes are directly applied to the cultivation substrate (Kerrison et al. 2018). Although twine seeding is the most common technique for kelp cultivation in Europe (Kerrison et al. 2020), it is labour-intensive and requires (costs and investments for) a hatchery facility (Forbord et al. 2020b, Boderskov et al. 2021). Direct seeding has been used with mixed results, with Mols-Mortensen et al. (2017) reporting successful cultivation with direct seeding at a sheltered, wave-exposed, and current-exposed locations, while they found a lower biomass yield for the current exposed location compared to the other two locations. Forbord et al. (2020b), on the other hand, found longer fronds and higher biomass yields with twine seeding compared to direct seeding at a sheltered nearshore location. The optimal seeding technique will therefore likely depend on the context.

In terms of species, we focus on native kelp species suitable for cultivation in North-West Europe: *S. latissima*, *Alaria esculenta*, and *Laminaria hyperborea* (Phaeophyceae) (Kerrison et al. 2015, Araújo et al. 2021). Integration with (shell)fish species could be beneficial for the environment and potentially increase seaweed yields. The integration of seaweed farming with (shell)fish species is often referred to as Integrated Multi-Trophic Aquaculture (IMTA) (Buck et al. 2018, Fossberg et al. 2018, Kleitou et al. 2018). A potential environmental benefit of this approach is the repurposing of waste from higher trophic species into valuable co-products (Chopin et al. 2001, Hughes and Black 2016, Buck et al. 2018). Studies also demonstrate an increase in macroalgae biomass yield in close proximity to fish (Kerrigan and Suckling 2018) and mussel farms (Hargrave et al. 2022). Finally, a way to reduce labour costs in European seaweed farms could be mechanization of seeding and harvesting (Tullberg et al. 2022, Jansen et al. 2023). As an additional benefit, mechanization would also enable upscaling to achieve an industrial scale (Tullberg et al. 2022, Albrecht 2023). Moreover, the use of purpose-built machines can contribute to the safety of workers on the

seaweed farm, which now often use equipment developed for other sectors, which in practice carries a risk (Makri et al. 2024).

### Post-harvest stages

We identify three post-harvest stages: processing, logistics, and sales markets. During processing, seaweed is prepared for storage or downstream applications (Zhu et al. 2021). Processing improves the quality of the seaweed for applications, e.g. in food (Zhu et al. 2021). Logistics include shipping resources and products from and to the right location. The markets for seaweed include food, feed, biostimulants, pharmaceuticals, and cosmetics markets (Araújo et al. 2021). Each might have different quality criteria, prices, and species preferences (Hafting et al. 2015, Araújo et al. 2021).

### Context variables

The choice of context variables is based on literature. The distance to the coast is likely to influence farm scale, as there is less space available nearshore (Tullberg et al. 2022). Seaweed species grow in a specific temperature and salinity range. A salinity of 33–35 psu is considered optimal for kelp species (Kerrison et al. 2015). The optimal temperature of *S. latissima* ranges from 5 to 15°C (Kerrison et al. 2015). When the water heats up to 20–24°C, most kelp species will die (Kerrison et al. 2015). Water depth is another important contextual factor as it influences mooring infrastructure design (Lin and Sayer 2015) and seaweed growth (Azevedo et al. 2019).

We focus on the abiotic factors as they shape ecosystems on a large scale and are comparatively steady or follow seasonal patterns over time (Benton 2009). Biotic factors vary considerably over time and have a rather local impact (Benton 2009), making their effect difficult to determine. Such results would therefore only be representative of a small fraction of the potential cultivation area.

One important aspect of the institutional environment is the administrative permission to use aquaculture areas in North-West Europe. The regulations are different for different European countries, while they are all influenced by broader EU directives such as the Marine Spatial Planning Directive (2014/89/EU), the Marine Strategy Framework Directive (2008/56/EC), the Water Framework Directive (2000/60/EC), the Alien Species Regulation (2014/1143/EU), and the Habitats Directive (92/43/EEC) (Barbier et al. 2019). The directives emphasize sustainability in the forms of protection of the coast and water, conservation of natural habitats, and prevention of the introduction and spread of invasive species (Barbier et al. 2019). In Europe the permitting process includes generally selecting a suitable cultivation site, conducting environmental impact assessments, and acquiring licences from relevant authorities. The specific procedures and authorities differ between countries within North-West Europe; therefore, the country where the cultivation site would be located impacts the permit process. Norway, for instance, has a long history of aquaculture and well-established regulations for seaweed cultivation (Barbier et al. 2019). In contrast, obtaining a permit in the Netherlands can be more complex due to the involvement of multiple authorities (Rijkswaterstaat, provinces, and municipalities) and the absence of a standardized protocol for permit approval (Rijksoverheid 2022).

Based on our conceptual framework, the identification of prospective seaweed systems requires decisions on various

**Table 1.** Three context descriptions used during the workshop

	Nearshore	Offshore single enterprise	Offshore in wind farm
Distance to coast	<1 km	20–40 km	25 km
Water depth	50–200 m	100 m	30–50 m
Water temperature	between 5°C and 16°C	between 6°C and 14°C	between 5°C and 20°C
Average salinity	35 psu ± 1 psu	34.5 psu ± 0.25 psu	33 psu ± 0.5 psu
Single or multi-use	Single enterprise	Single enterprise	In a wind farm
Other water conditions <sup>a</sup>	Assumed to be suitable for seaweed cultivation	Assumed to be suitable for seaweed cultivation	Assumed to be suitable for seaweed cultivation
Country	Norway	UK east coast	The Netherlands

<sup>a</sup>including nutrient availability.

Source: Compiled based on Seatemperature.info (2023a), Seatemperature.info (2023b), Seatemperature.info (2023c), and Seatemperature.info (2023d) for water temperature, Quante et al. (2016) for salinity, and Marineregions.org (2023) for water depth.

variables in the cultivation design and will involve interdependencies for cultivation and post-harvesting. The framework hence underlines the need for an integrated approach when identifying prospective seaweed systems.

## Methodology

Our methodological approach consists of two steps: an expert workshop in which participants gave their opinion on prospective seaweed systems conditional on the provided context and the collection of written feedback from the participants to validate the outcomes.

### Expert workshop

Participatory workshops are often organized to produce future scenarios (Demeter et al. 2009, Nygrén 2019). We held a participatory workshop to collect diverse perspectives from experts on prospective seaweed systems for the near future in North-West Europe. The workshop setup was based on the World Café method, which consists of seven design principles: (i) set the context; (ii) create hospitable space; (iii) explore questions that matter; (iv) encourage everyone's contribution; (v) cross-pollinate and connect diverse perspectives; (vi) listen together for patterns, insights, and deeper questions; and (vii) harvest and share collective discoveries (Brown and Isaacs 2005). The World Café method has the advantage of encouraging discussion and mutual learning, thereby enhancing participant involvement and generating valuable insights (Löhr et al. 2020). The focus of the workshop was on identifying prospective seaweed farming systems for three different pre-defined contexts by making choices on the cultivation site variables (scale, substrate, seeding technique, species, integration with (shell)fish species, and level of automation). The workshop also served to determine challenges, risks, and obstacles for each of the seaweed systems, including potential solutions. We define risk as uncertainty that matters (Hardaker et al. 2015), implying the possibility of negative consequences for the seaweed farm(er) or others. Obstacles are issues or concerns that hinder the system from being implemented in practice.

As a starting point, we used three pre-defined operational contexts that have been informed by our conceptual framework: (i) nearshore, (ii) offshore single enterprise, and (iii) offshore in a wind farm (Table 1). We chose these three as they represent contexts of systems that already exist and are therefore practically relevant while differing in their abiotic factors, distance to the coast, and institutional environment (cf. Fig. 1). Moreover, one system is combined with (or even integrated in)

a wind farm, while two focused on seaweed cultivation only, i.e. single enterprise. We attributed the context descriptions to three actual locations to help participants imagine the contexts better: (i) nearshore in Norway, (ii) offshore from the east coast of the UK, and (iii) offshore within a Dutch wind farm. We visualized these locations on a map, which was presented during the workshop (Supplementary Appendix A). Finally, the implications of having the seaweed farm within a wind farm were added, as this is politically relevant and might have impacts on what is possible in the seaweed system, e.g. regarding safety rules (van den Burg et al. 2020).

In the workshop, 9 out of 39 invited experts participated. (Reasons for not participating include perceived lack of knowledge and not being able to participate on the chosen workshop day. Not all invited experts gave reasons for not being able to attend.) These participants included two seaweed farmers; four supply chain stakeholders involved in seaweed seeding (one), technology development (two), and branding (one); and seaweed researchers (three). They were based in the Netherlands, Belgium, and Ireland. The workshop format was hybrid, with two participants attending physically and seven joining remotely. All participants were briefed about the objectives of the workshop and the data handling and gave informed consent.

The workshop consisted of four phases: an introductory presentation, two rounds of group discussion, and a plenary session. In the first phase (introduction), we outlined the four components of the workshop: (i) the workshop's objectives, (ii) a description of the three different contexts, (iii) the cultivation site decisions to be made, which were visually illustrated (Supplementary Appendix B), and (iv) the questions to be addressed during the subsequent group discussions. These questions explored prospective seaweed systems, given the specific context by identifying the optimal cultivation site variables. Next, the participants discussed challenges related to logistics, processing, and sales markets and were asked what type of risks they foresee for the identified systems. Finally, the participants were asked to think about 'What obstacles are there to get to those farming systems?' and 'What needs to be done to get to those farming systems?' to identify solutions.

We had three rounds of discussions: two with breakout sessions and one plenary discussion. For the breakout sessions, participants were divided into three groups. Each group discussed one context per session, and then turned to another context in the next session. Each breakout session was moderated by one of the co-authors. Notes were taken by other colleagues. In the first breakout session, participants had to choose between two or three options for each of the cultivation site variables, which they perceived as optimal for their

system (Supplementary Appendix B). Next to this, they discussed the challenges, risks, obstacles, and solutions regarding these risks and obstacles for the system. In the second round of group discussions, the same groups reconvened in their breakout sessions and followed the same procedure as in the first round. In this round, the groups discussed a different context than in the first round. This second round was organized for validation and possible adjustments of the outcomes of the first round. The moderator explained the findings from the previous round serving as a starting point for the second round. We finalized the workshop with a plenary session where the outcomes of the discussions were shared by the moderators of the three groups. The purpose of this plenary session was to bring the outcomes of the two rounds of breakouts together and inform the participants about the overall findings.

### Validation via written feedback

The outcomes of the workshop were summarized in tables, including the final choices on the cultivation variables and the supporting arguments, as well as the challenges, risks, obstacles, and solutions identified for each context. These tables were distributed among the workshop participants and experts who were unable to attend. We asked them to indicate whether they agree, partially agree, or disagree with 175 statements based on the outcomes of the workshop (Supplementary Appendix C). Among these statements, 104 were about the cultivation site variables, 21 about the post-harvesting stage, 11 about risks, 10 about obstacles, and 29 about solutions.

Seven of the workshop participants and one expert who had not attended provided feedback. Some participants did not have the expertise on all fields and left some answers open or put a question mark. These answers were not included in the validation. The validation was done using a scoring system similar to the net promoter score (NPS) (Net Promoter Score® 2024). NPS is commonly used to index the willingness of customers to recommend a product or service to someone else. We used it as an index to indicate how much participants ‘promoted’ a certain outcome. The score indicates the share of participants agreeing minus the share of participants disagreeing. The participants who indicated to partially agree were considered neutral for this calculation and were included in the total number of participants when calculating the shares. We only calculated this validation score for the cultivation stage, as this level yielded the most detailed answers during the workshop.

## Results

In line with our conceptual framework, we summarize the findings for the three identified prospective seaweed systems regarding the six variables of cultivation (scale, substrate, seeding technique, species, integration with (shell)fish species, and automation level) and the three post-harvest stages (processing, logistics, and sales market). In the section ‘Overview of the prospective seaweed systems’, we summarize the outcomes combined with the agreement scores for the cultivation variables. Further details per system are described in the sections ‘Prospective seaweed system “Nearshore” (Fig. 2)’, ‘Prospective seaweed system “Offshore single enterprise” (Fig. 3)’, and ‘Prospective seaweed system “Offshore in wind farm”

(Fig. 4)’, each supported by a visualization (cf. Figs 2–4) with the highlights per prospective system.

### Overview of the prospective seaweed systems

For nearshore cultivation, participants considered the following characteristics optimal: (i) small scale (<10 ha), (ii) single lines, (iii) twine seeding, (iv) multiple suitable species, (v) cultivation near (shell)fish species, and (vi) full mechanization. For the cultivation site of the offshore single enterprise system, participants opted for: (i) large scale (>100 ha), (ii) single lines, (iii) direct seeding, (iv) multiple suitable species, (v) not integrated with (shell)fish species, and (vi) full mechanization. Offshore cultivation site in a wind farm yielded the following characteristics: (i) large scale (>100 ha), (ii) nets, (iii) direct seeding, (iv) multiple suitable species, (v) possible integration with shellfish cultivation, and (vi) full mechanization (Table 2).

In all three contexts, the participants opted for cultivating multiple species and a high level of automation. The optimal scale, substrate choice, integration with (shell)fish species, and seeding technique were different. However, there was substantial variation in agreement levels for each of the cultivation choices (Table 2).

### Details per prospective system

#### Prospective seaweed system ‘Nearshore’ (Fig. 2)

Most participants agreed that the ‘Nearshore’ system (<1 km from the coast) ideally operates at a small scale—<10 ha—and could be divided into smaller modules (Fig. 2). For this system, the experts agreed most clearly on the use of lines as the optimal substrate (Table 2). Lines were seen as the cheapest option while also avoiding the potential issue of self-shading, which could happen when using nets. The seeding technique most participants favoured was twine seeding, as this seeding technology is established for small-scale, nearshore systems. Direct seeding was mentioned to be less reliant since a large and variable proportion of seeding material detaches from cultivation lines. Besides variable and reduced yields, participants feared potential impact of detached seeding material on natural coastlines and their natural seaweed biodiversity. Since twine seeding incurs less detachment of seeding material, it was considered the safer option.

Multiple suitable species were identified: *S. latissima*, *A. esculenta*, *Laminaria digitata*, and—if the scope would be extended to include red and green seaweeds—also the red seaweed species *Palmaria palmata* (Rhodophyta). The first, *S. latissima*, was considered suitable based on pre-existing knowledge and expertise on its cultivation in Europe. The second, *A. esculenta*, was argued to give a higher yield in some sites compared to *S. latissima* and *A. esculenta* was preferred for its taste. While *L. hyperborea* was mentioned to grow slowly but yield a good quality of alginate (alginates are extracted from brown seaweeds and are commonly used in the creation of coatings and films because of their gelling properties (Jayakody et al., 2022)), most of the participants agreed that it is not the preferable species for this system. *Laminaria digitata* was mentioned to be economically preferred over *L. hyperborea*. *Palmaria palmata* was mentioned as an interesting species specifically for Norway.

Participants perceived cultivating seaweed near fish and shellfish farms as preferable over integrating these types of aquaculture in one farm. The latter was perceived as too chal-

**Table 2.** Optimal cultivation site decisions per seaweed system: agreement levels indicated by Net Promotor Score (green is most agreement, red is most disagreement)

Context	Nearshore system	Offshore single enterprise	Offshore in wind farm
Scale	Small-scale	Large-scale	Large-scale
Substrate	Single lines	Single lines	Nets
Seeding technique	Twine seeding	Direct seeding	Direct seeding
Species	Multiple species	Multiple species	Multiple species
Integration with (shell)fish species	No integration, but near fish and shellfish species	No integration	Indifferent about integration; shellfish is preferred to fish
Automation level	Full mechanisation	Full mechanisation	Full mechanisation

We use the Net Promoter Score as a scoring system for the colours in this table to indicate how many participants agreed with the final outcomes. The score indicates the share of participants agreeing minus the share of participants disagreeing. The people who partially agreed were included in the total number of participants, i.e. in the denominator. The colours align with the following agreement scores: 100; 85.71; 71.42; 57.14; 42.85; 28.57.

lenging due to differences in expertise. Seaweed cultivation near (shell)fish species would, however, be beneficial in terms of nutrient availability while allowing each farmer to maintain their specialization. Mechanization was considered important throughout all levels of farming, including seeding, harvesting, and processing. Remote automated monitoring with sensors and satellite data was mentioned to improve insights into volumes and optimal harvest time. However, the need for mechanization is perceived as less important when operating on a small scale, which is reflected in the limited consensus for mechanization by the participants.

A challenge of seaweed production in general is that it needs to be processed quickly after harvesting due to its perishability. Processing of seaweed starts with washing, whereafter it, depending on the application, can be dried, frozen, salted, boiled, or fermented to extend the shelf life. Participants recommended washing (as a first processing step) the seaweed on ships immediately after harvest and further processing on land. Another approach is by jointly organizing the logistics of multiple small-scale farms. A ship could, e.g. go from farm to farm collecting the seaweed and process it together.

Due to relatively high production costs, applications in high-value markets were considered most realistic. These markets include extracts for pharmaceuticals, nutraceuticals, cosmetics, food and feed ingredients, and furthermore for human food, bioplastics, and bio-stimulants. The biofuel and fertilizer markets were not regarded as attractive for this seaweed system as the cultivation is too expensive for these markets.

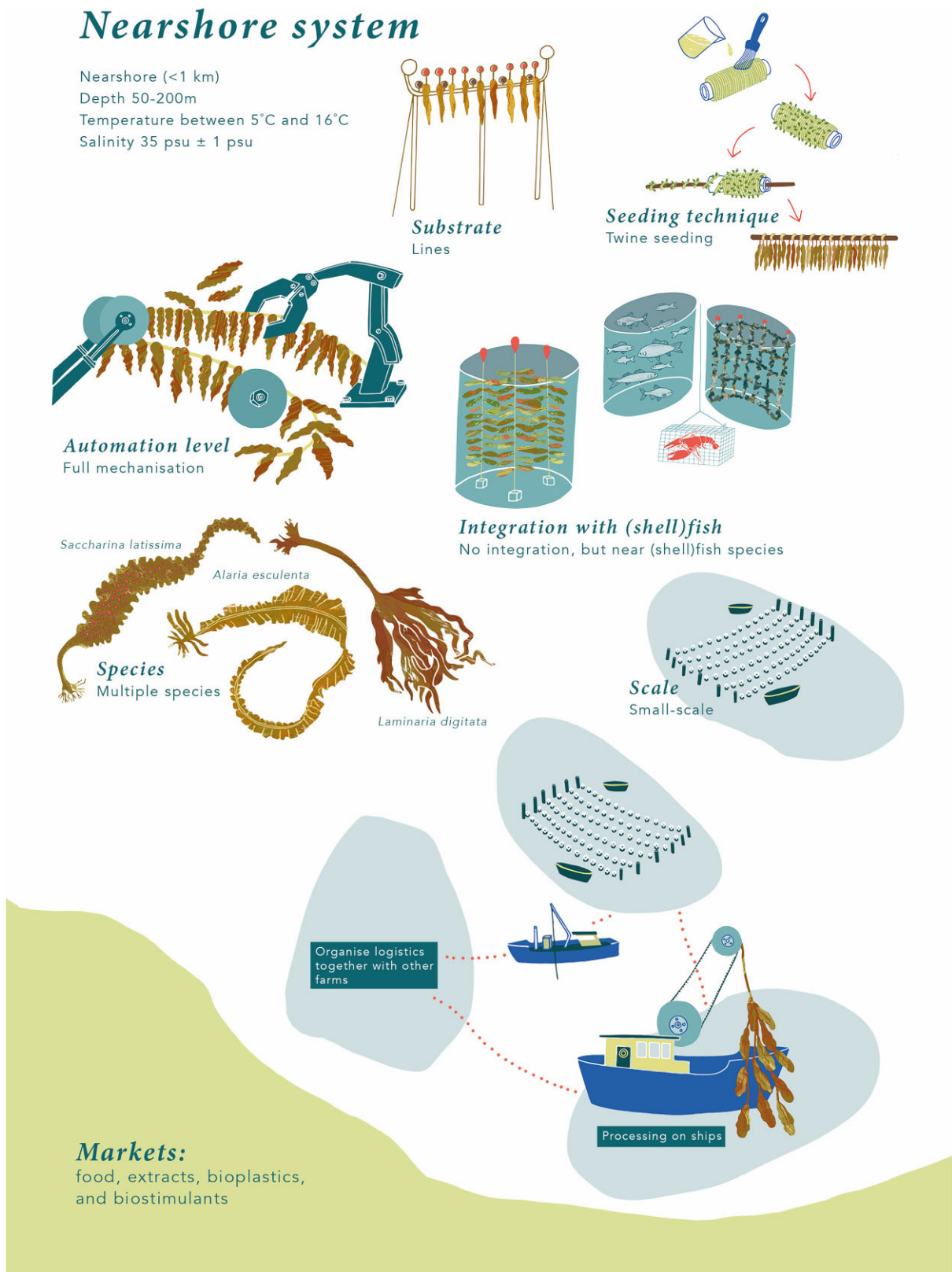
Two production risks and one financial risk were mentioned for this seaweed system. First, the risks related to keeping the rigs in place. There is a risk that the lines used as substrate can get entangled. Second, there is a risk of diseases and pests. For the kelp species in our studies, these could be bac-

terial infections like the rot disease, oomycetes that decrease biomass and quality, and galls or twisted stipes caused by endophytic brown algae like *Laminarionema elsbetiae* (Bernard 2018, Bernard et al. 2019). This risk was mentioned to be reduced by having farms cultivating different seaweed species, which makes the optimal species outcome ‘multiple species’. Finally, investors generally consider seaweed farming as risky, which reduces their appetite to invest. An obstacle for implementing the system in practice mentioned was to attain farm profitability, since the operational costs are very high compared to the low market value.

Solutions to overcome this profitability obstacle involve product development, awareness creation, and the engagement of fishing communities by reducing costs with equipment (ships or machines) sharing. Participants mentioned that it is necessary that new and profitable products should be brought to the market. Education and awareness creation were found to be important to make the general public more aware of seaweed to increase the demand. This was seen as a role for the government or the European seaweed sector as a whole, e.g. by organizing awareness-creating campaigns, since a single seaweed farmer does not have the resources to make a difference in this regard.

### Prospective seaweed system ‘Offshore single enterprise’ (Fig. 3)

Almost all participants agreed that the ‘Offshore single enterprise’ system (20–40 km from the coast) would only be economically feasible on a large scale (>100 ha) due to the high costs of shipping and substantial investments required for mooring and anchoring (Table 2). For this system, the use of single lines as a substrate was considered optimal. Across all decisions to be made for this system, there was the least con-



**Figure 2.** Visualization of prospective seaweed system 'Nearshore'.

sensus on which seeding technique to use. Direct seeding offers higher flexibility in timing compared to twine seeding, which means seeding can occur when weather conditions are optimal. This flexibility was considered crucial offshore, where

storms or other rough conditions hinder operations. However, it was mentioned that the seeding material also detaches faster with the direct seeding method under rougher water conditions.

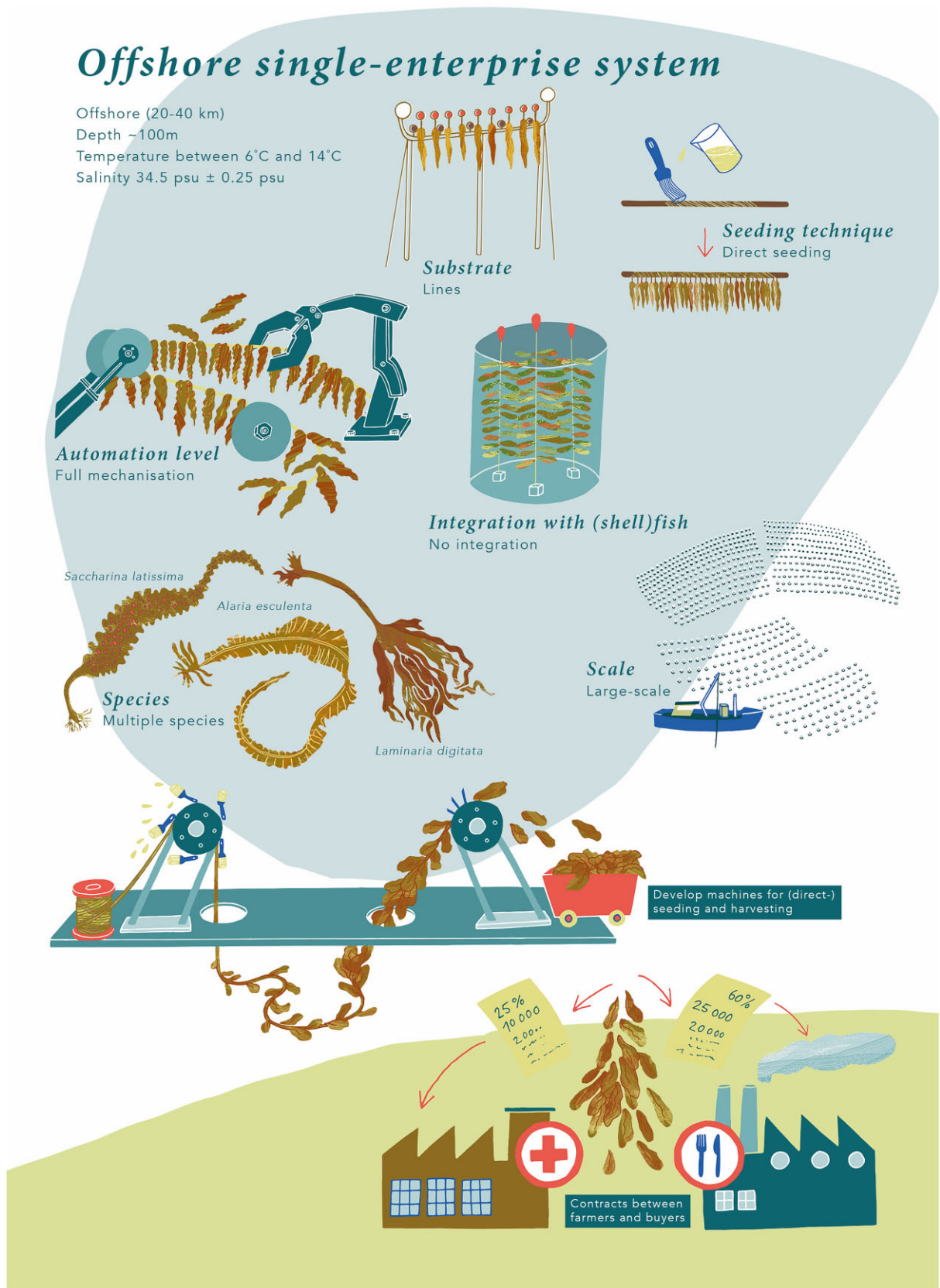


Figure 3. Visualization of prospective seaweed system 'Offshore single enterprise'.

# Offshore in wind farm system

Offshore (~25 km)  
 Depth 30-50m  
 Temperature between 5°C and 20°C  
 Salinity 33 psu ± 0.5 psu  
 In windfarm

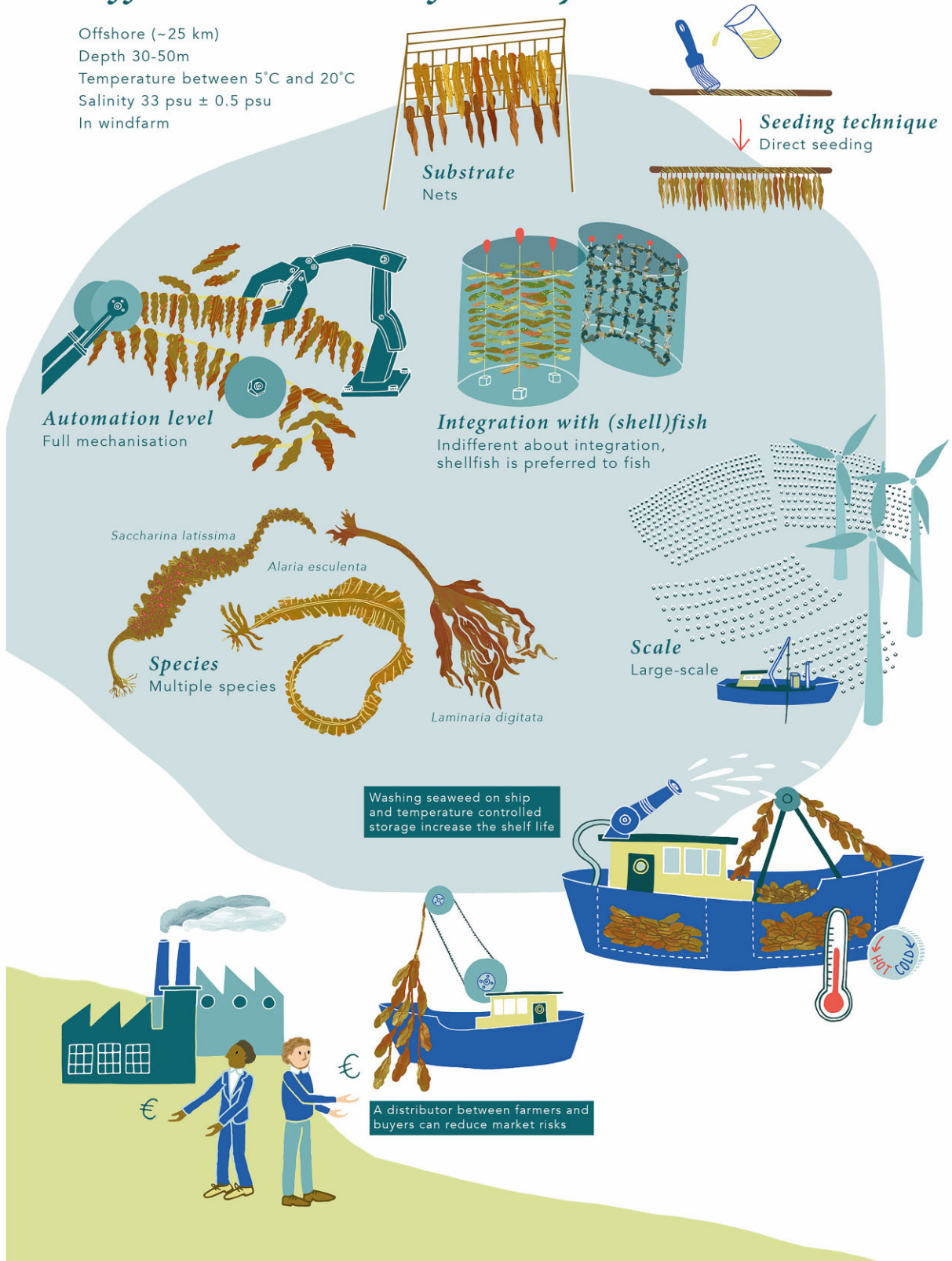


Figure 4. Visualization of prospective seaweed system 'Offshore in wind farm'.

Again, multiple suitable species were identified: *S. latissima*, *A. esculenta*, and *L. digitata*. The first, *S. latissima*, was perceived as promising based on previous experience. The second, *A. esculenta*, was also pointed out to be highly successful in the past in terms of robustness, which is necessary when cultivating offshore. *Alaria esculenta* attaches better than *S. latissima* and has good market and product opportunities. A downside mentioned, however, was that it is an annual species. This restricts the possibility of multiple harvests from a single crop, and thus of reducing seeding costs. *Laminaria digitata* was mentioned to naturally occur in exposed conditions and was therefore seen as the most suitable species for offshore cultivation.

An integration with (shell)fish species was mentioned to potentially be favourable in an offshore setting, to improve the availability of nutrients offshore and increase attractiveness for investors. At the same time, strict regulations offshore could also complicate such integrations. Additionally, participants mentioned that fish and seaweed farming are completely different forms of aquaculture, and therefore, it is better to first focus only on seaweed to have a successful seaweed system. Integrating seaweed cultivation with (shell)fish species was ultimately considered as not ideal for this seaweed system (Fig. 3). All but one participant preferred full mechanization for this system because of high labour costs in North-West Europe (Table 2).

For this seaweed system, multiple challenges were mentioned. The first logistical challenge is securing a ship that meets the requirements for offshore travel, which participants noted are in limited availability. Another challenge is related to the size of the seaweed system. Large-scale seaweed systems require (investments in) a large local processing facility. The final challenge is uncertainty around the financial reward for successful, big-volume harvests. The participants mentioned that customer interest and pricing should be established before seeding.

A production risk for this seaweed system is the limited nutrient availability offshore, which might be too little to optimally cultivate seaweed. The market risk is in line with the challenge of having large quantities of unsold seaweed. This unsold seaweed has economic consequences in storage costs, e.g. energy costs of freezing. Finally, a financial risk was mentioned, since large investments are necessary for this large-scale offshore seaweed system.

In order to implement this system in practice, participants expected different obstacles. These obstacles include the access to sufficient local seed stock, which depends on the availability of local fertile sporophytes from natural resources and the accessibility to get the sporophytes. Besides, licensing, permits, and building the infrastructure were mentioned as obstacles for this farming system. Moreover, finding a suitable ship with an experienced crew at the right time was seen as an obstacle.

One of the solutions would be to rent pre-licensed and pre-equipped sites. Participants argued that this lowers the entry barrier for farmers, as a large company takes on the investment costs. Market risks could be solved via contracts between buyers and farmers, stipulating the amount of produce and when, and at what price it would be delivered.

Improving the attachment of direct seeding, i.e. by improving the binder, would also increase the feasibility of this seaweed system. Furthermore, participants stressed the need to further develop machines for direct seeding and harvesting

and, finally, for governments to support starting farmers in providing information about cultivation sites, e.g. by providing unexploded ordnance surveys (Howard et al. 2012) to detect ferrous anomalies in the ground.

#### Prospective seaweed system ‘Offshore in wind farm’ (Fig. 4)

Almost all participants agreed that the ‘Offshore in wind farm’ system (25 km from the coast) would only be economically feasible on a large scale (>100 ha) (Table 2). To optimize efficiency, the participants suggested making maximal use of the available space for seaweed cultivation in a wind farm setting. There was disagreement on the best substrate choice for this system (Table 2). Some participants argued that nets facilitate scalability and make use of the available space more efficiently due to the use of depth, but others disagreed. However, there was consensus that nets are well-suited for deployment in deep waters, particularly in low turbidity conditions where the sunlight can penetrate to lower parts of the net. Direct seeding emerged as the optimal seeding technique for this system, as it is compatible with upscaling and the use of nets (Fig. 4). However, challenges arise offshore in the Dutch North Sea due to strong currents, which may cause rapid disintegration of the binder used in direct seeding, leading to unpredictable yields. Further improvement of binders and substrates is essential to enable the efficient use of direct seeding in such locations.

Multiple suitable seaweed species were identified. However, the species *A. esculenta*, *L. hyperborea*, and *L. digitata* do not naturally occur in the Netherlands, and their cultivation is currently not allowed. Therefore, *S. latissima* would be the preferred kelp species to cultivate in this farming system if the system would be located in the Netherlands. Participants argued that, ideally, multiple species and also different types of brown, green, and red seaweeds are all co-cultivated.

Participants were indifferent about integrating seaweed with (shell)fish cultivation (Table 2). Seaweed cultivation integrated with shellfish was considered a realistic option for this system, especially because of the established shellfish sector in the Netherlands. Moreover, participants argued that integrating aquaculture may offer benefits from a marketing perspective. Most participants believed that fish or shellfish can be marketed as sustainably produced when co-cultivated with seaweed. Co-cultivation with fish is considered less realistic for this context due to temperature fluctuations in the North Sea. Most participants preferred full mechanization for this large-scale system, particularly for labour intensive tasks (Table 2), and it was seen as a prerequisite for increasing the economic feasibility of the system. Some participants argued that monitoring still needs to be conducted in person, while others suggested that this too could be automated. The main focus of automation would be seeding and harvesting.

This ‘offshore in wind farm’ system shares some of the challenges of the ‘offshore single enterprise’ system, namely the availability of ships and the time it takes to bring harvested seaweed from an offshore cultivation site to the coast.

Production risks mentioned were the variation in success between different offshore cultivation systems and the risk of early detachment after seeding with the direct seeding method. A market risk mentioned was that farmers may fall in between small-scale, high-value markets (i.e. food) and the large bio-stimulant market with a lower value.

The participants identified seeding and harvesting as obstacles to scaling up to this system in practice. An additional bottleneck is sourcing sufficient local seeding material to cultivate on a large scale. Finally, strict regulations within wind farm areas could restrict the design of the seaweed system.

To overcome the impacts of long travel times on seaweed quality, temperature-controlled wet storage on ships was mentioned to be a solution. Also, washing the seaweed immediately on the ship could increase shelf life. Ship availability issues would ideally be solved by sharing with a sector that does not need the ships at the same time. Furthermore, to solve the obstacle of early detachment of the seeding material with direct seeding, one participant mentioned the idea to seed the substrates first nearshore. After the seeding material becomes more robust, the nets can be moved to the rougher offshore location. Moreover, participants mentioned distributors could help overcome certain market risks. Renting prelicensed and pre-equipped sites owned by the wind farms could help seaweed farmers overcome entry barriers by reducing investment costs. However, not all participants were in favour of granting such power to energy companies. Additionally, a solution to overcome the obstacle of scaling due to seeding and harvesting, the participants suggested developing seeding and harvesting machines that are scalable. Finally, many participants advocated that subsidies are essential for developing the offshore seaweed sector.

## Discussion

### Comparison with existing cultivation systems

Based on input from experts, three prospective seaweed systems were identified for North-West European waters. These three systems differ based on the distinct contexts presented to the participants during the workshop, indicating that different contexts necessitate unique system setups. For each context, we find that there is a window of opportunity for seaweed farms given a variety of choices with regard to the cultivation site and post-harvest stages. This study aids in identifying these opportunities and highlights the challenges associated with each system. Certain challenges and risks identified for specific systems are likely applicable to the other systems as well. These include the risk of diseases, which could be increased by monoculture, as noted for the nearshore system. For the two offshore systems, the optimal outcome was also to cultivate multiple species, while in large-scale systems, the risk of diseases could be even larger. Additionally, the financial risk perceived by investors, who view seaweed farming generally as risky—a concern highlighted for the nearshore system—may be even more relevant for the two offshore systems.

Some identified combinations of cultivation variables for the systems already exist in operational seaweed farms. For instance, there are small-scale nearshore seaweed farms in Norway (Forbord et al. 2020a), and offshore systems integrated with wind farms (NSF 2024, Vattenfall 2024)—albeit just a few. Current seaweed farms have challenges with profitability, especially for an offshore wind farm system. van den Burg et al. (2016) found that this would not be economically feasible at the time with given costs and prices. Future research should be done to examine whether cost reductions with direct seeding and mechanization (considered optimal for this system in our study) will make this system economically feasible.

Hasselström et al. (2020) argue that large-scale seaweed cultivation in Sweden could become profitable, especially when ecosystem services would be monetized. Menzies et al. (2021) studied small- to medium-scale seaweed farms on the West Coast of Scotland, where they found viable scenarios in terms of achieving payback of investments between 3 and 5 years. However, for the small-scale (8 ha) farm, they found that this would only be feasible with prices over €1200 (>1000 GBP) per tonne wet weight, while buyers might not want to pay this. Our findings on the logistic challenges also reflect previous findings, e.g. by Araújo et al. (2021) and Cerca et al. (2024), as do the potential of the direct seeding technique (Kerrison et al. 2020, Boderskov et al. 2021) and the need for mechanization (Tullberg et al. 2022, Jansen et al. 2023). Thus, the components of the identified prospective seaweed systems match with existing systems and practices in North-West Europe.

### Reflection on methodology

Our study approach has limitations. First, while expert workshops lead to informed responses from knowledgeable individuals, this could also introduce bias. For instance, participants might prefer techniques, routines, or choices, with which they are familiar, over the choices they are less familiar with. This may create path dependency, resulting in reconfirmation of current systems rather than ideas for alternative systems (Paas, Accatino et al. 2021). We circumvented this as much as possible by including researchers and other actors with no direct stake in current systems or workshop outcomes. Secondly, our study relies on ex-ante expectations rather than ex-post outcomes, which introduces a risk of subjectivity bias. The outcomes are based on expectations and predictions of experts regarding what is optimal, rather than on objective data like yield, costs, or profits. To minimize this subjectivity bias, we conducted two rounds of group discussions and a written feedback round. Multiple rounds of expert elicitation generally lead to more precise estimations (Dalkey and Helmer 1963, Rowe and Wright 2001). Subjectivity bias might be compounded by a small number of participants (Paas et al. 2021). However, we had to work with a limited number of sector experts since the seaweed sector in North-West Europe is currently small, with approximately only 33 companies cultivating seaweed at sea, 10 companies in breeding and propagating (seed production), 29 companies in infrastructure and equipment, 27 companies in the processing stage, 10 companies in the distribution stage, and 237 companies in applications (Vazquez Calderon and Sanchez Lopez 2022, Hermans 2024).

### How to use the prospective seaweed systems?

Our results demonstrate the variation in seaweed systems across North-West Europe, i.e. there is no single optimal seaweed system for the region. Gaining insights into the different optimal cultivation choices, challenges, risks, and obstacles for seaweed systems in different contexts in North-West Europe is beneficial for the European seaweed sector. This way, the diversity between the optimal choices and solutions to implement the systems can be tailored to the specific context. We expect that the prospective seaweed systems are useful for several user groups. The first user group consists of technology developers looking to improve the direct seeding method (WUR 2022). Two of the three prospective systems involve direct seeding which seems to have a lot of poten-

tial in making the systems economically feasible, but are currently associated with significant losses of seeding material. Additionally, the development of machines for seeding and harvesting should be advanced to support further automation. The second user group are seaweed farmers. Farmers can draw inspiration for different farming options tailored to various contexts. Third, financial institutes, e.g. banks, can use the prospective systems to categorize seaweed farms and create benchmarks for economic performance. Currently, banks lack knowledge on how to evaluate a seaweed business with regard to capital requirements and best practices in operations. Benchmarks based on our prospective systems can be used to assess the financial risks of a seaweed farm by comparing it to similar seaweed systems. This can provide the basis for funding approval to farmers. Standardization institutes, e.g. CEN, comprise the fourth user group (CEN 2024). They can use the prospective systems to capture the differences in possibilities for European seaweed farms. The prospective systems can serve as inputs in ongoing initiatives to establish recommended seaweed farm design standards (Globeafoodalliance 2022, NSF 2023). Such standards foster trust among producers, insurers, and within the value chain (Sensalg 2023). We recommend that standardization institutes acknowledge the differences between various systems and develop separate standards for different systems. The final user group consists of policymakers, who can utilize the prospective systems to nuance their debates on visions for the seaweed sector in Europe by discussing what system they would like to have and stimulate these. Each prospective system has its specific challenges. Systems can be stimulated by funding research and innovation tailored to these challenges per system.

## Conclusions

We identified three prospective seaweed systems, each covering cultivation and post-harvest stages. The first prospective system, i.e. ‘Nearshore’, is characterized through its small scale (<10 ha), the use of twine seeding on lines, and full mechanization of all cultivation steps. It has multiple suitable species, and it is recommended to be close to (shell)fish species to increase nutrient uptake. Regarding the post-harvest stage, the logistics of multiple small-scale farms are ideally organized together. The second prospective system, i.e. ‘Offshore single enterprise’, is characterized by its large scale (>100 ha), the use of direct seeding on lines, and full mechanization of all cultivation steps. It has multiple suitable species and operates without the integration with (shell)fish species, as this complicates the system. Because of the offshore location, this system faces the logistical challenge of suitable ship availability. The third prospective system, i.e. ‘Offshore in wind farm’, also features large-scale (>100 ha) operations and direct seeding, but utilizes nets instead of lines as substrate. Moreover, the system has ideally multiple species, offers the potential for integration with shellfish cultivation, and is fully mechanized throughout all cultivation stages. A distributor or contractual agreements between farms and buyers can help to reduce the market risk of having large quantities of unsold seaweed.

The three identified prospective systems illustrate the variety of possible seaweed systems for different contexts in North-West Europe. We therefore recommend that all parties interested in seaweed cultivation in this region, such as financial institutes, standardization institutes, and policymak-

ers, rely on this diversified view. We expect that this will contribute to a more nuanced debate about seaweed systems and the achievement of a strong seaweed sector in North-West European waters.

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## Author contributions

Conceptualization: L.Z., S.B., T.K., N.M., and M.M.; Data collection: L.Z., S.B., T.K., N.M., and M.M.; Data analysis: L.Z. and M.K.; Writing original draft: L.Z.; Writing—review & editing: L.Z., S.B., T.K., M.K., N.M., and M.M.

## Supplementary data

Supplementary data is available at *ICES Journal of Marine Science* online.

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## Data availability

The data underlying this article will be shared on reasonable request to the corresponding author.

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