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# Responsible supply systems for macroalgae: Upscaling seaweed cultivation in Ireland

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ABSTRACT

To address societal challenges and attend to the increasing demand for seaweed while avoiding the over-exploitation of wild resources, the future expansion of the Irish seaweed industry depends on upscaling macroalgal cultivation. Through an interdisciplinary research approach, this study aimed to conduct an in-depth investigation of the prospects of upscaling seaweed aquaculture in Ireland through the lens of sustainability management. The identification of responsibilities of emerging enterprises was aligned with socio-ecological dimensions of sustainability and found to be related to: 1) the natural environment, 2) the development of rural coastal communities, 3) the engagement with local actors and 4) the customer segment. Moreover, seaweed cultivation still faces many uncertainties and bottlenecks from the operational up to institutional levels. Distinct from seaweed collected from the wild, cultivated seaweed has more phases added to the supply chain cycle. This includes, for example, the optimal site selection, the granting of an aquaculture licence and potentially social licence to operate, seed supply, and optimal timing for cultivation or harvest depending on the species, processing capacity and end-uses. The results contribute to an enhanced and holistic understanding of macroalgal cultivation in Ireland, as well as the social responsibility of emerging enterprises over socio-ecological systems and for the establishment of new supply chains based on seaweed. This can help to guide better decision-making of prospective growers, certification bodies, and policymakers in Ireland and beyond.

## 1. Introduction

The cultivation of seaweed (marine macroalgae) has been gaining increasing scientific and societal recognition for its potential to contribute to sustainability targets such as climate change mitigation, ecosystems restoration and food security (Duarte et al., 2021). Within the European Union (EU), the expansion of the seaweed industry is supported by policy strategies in alignment with the European Green Deal and the transition to a 'circular blue bioeconomy' (European Commission, 2018; European Commission, 2019). This includes a recently launched platform to promote the production and use of algae in Europe (European Commission, 2022a). Based on these potentials, an increasing number of algae-based companies have been founded and a broad interest has developed in the sourcing of seaweed biomass for multiple applications, including food and feed, pharmaceuticals, cosmetics, bioplastics, bioenergy and biofuels (Kraan, 2020). The number of new algae-based companies has increased by 150% in the last decade (Araújo, 2019) and investments in seaweed doubled from 2020 to 2021 with the largest amount of deals and start-ups emerging from Europe (Phyconomy, 2022). However, the extent of seaweed cultivation is still small in Europe and this industry depends largely on the harvest of seaweed from the wild. While the demand for macroalgae has been constantly increasing over the last decades, about 99% of the global supply of cultivated seaweed is still derived from countries in Asia (Jagtap and Meena, 2022; Cai, 2021).

While Ireland is among the largest suppliers of marine macroalgae in Europe, producing about 30,000 (wet) tonnes of seaweed every year, seaweed cultivation represents less than 1% of this total volume (FAO, 2021). The wild collection of seaweed species such as *Ascophyllum nodosum* reaches the largest share of collected and processed seaweed, in an industry built on hundreds of years of hand-harvesting traditions, supporting rural coastal communities (Araújo, 2019; Mac Monagail et al., 2017). Pilot projects and small sites exist for the cultivation of kelps (brown macroalgae) species such as *Alaria esculenta, Saccharina latissima* and *Laminaria digitata*, as well as red seaweed species such as *Palmaria palmata* (Monagail and Morrison, 2020). While the supply of

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cultivated seaweed is still lacking, the number of Irish seaweed companies has been increasing from 12 to 43 in a time frame of 15 years (Bord Iascaigh Mhara, 2020; Marine Institute, 2006a, 2006b). Government grants have been awarded to assist potential seaweed growers in the development of this marine sector and within sustainable aquaculture schemes (Government of Ireland, 2021a; Government of Ireland, 2019; Government of Ireland, 2018). However, macroalgal cultivation and the establishment of new supply chains involve numerous bottlenecks.

Among the challenges are the difficulties in licensing procedures (Camarena-Gómez et al., 2022), the lack of regulation for seaweed products (Lähteenmäki-Uutela et al., 2021), unsettled societal responses and acceptance of cultivation sites (Billing et al., 2021), as well as additional technical difficulties from offshore systems (Bak et al., 2020). It is also often the case that new applications for aquaculture licenses need to provide a full business plan, imposing additional managerial challenges to Small and Medium Enterprises (SMEs), which comprise the large representation of aquaculture businesses in Ireland as well as the broad EU (Bord Iascaigh Mhara, 2022; European Commission, 2021). These challenges may hinder the uptake in seaweed cultivation and the creation of businesses that are ultimately contributing to sustainability targets and therefore committed to establishing more responsible supply chains for seaweed. Thus, this study aimed to conduct an in-depth investigation of the prospects of upscaling seaweed cultivation in Ireland, including socio-ecological dimensions related to the establishment of responsible businesses and supply chains. The following question leads the research process: *how can seaweed aquaculture be upscaled in Ireland considering the social responsibilities of emerging enterprises?*

Following theoretical and conceptual grounds of aquaculture innovation (Joffre et al., 2017), sustainable business models (SBM) and supply chains (Wieland, 2020; Lüdeke-Freund et al., 2016), we argue that seaweed growers occupy the position of entrepreneurs and have, therefore, a fundamental role in shaping innovations and sustainable transformations in aquacultural systems. To the best knowledge of the authors, this paper represents the first study analysing seaweed cultivation from a sustainability management perspective. We provide in Table 1 the definitions of the main concepts used to facilitate the dialogue between disciplines. The results contribute to advancing the discussion regarding future directions of the Irish seaweed industry but also to broader settings. The analysis based on empirical data and co-production of knowledge with seaweed growers intends to produce results that can meaningfully impact the developments of this emerging sector in the European context. This could help to guide better decision-making of practitioners, entrepreneurs, policymakers, and certification schemes, as well as provide new grounds for future research.

**Table 1**
Definition of the concepts used in this study.

| Concept | Definition |
|---|---|
| *Classification of seaweed (marine macroalgae)* | *Rhodophyta* (red algae), *Phaeophyta* (brown algae) and *Chlorophyta* (green algae). Within those groups, each species has different variations in biochemical composition and therefore may have different applications and end-uses (Zhu et al., 2022). |
| *Seaweed Supply Chains* | Following Wieland (2020) and Mulyati and Geldermann (2017)'s work, we define it as a dynamic and adaptative system comprising several phases and stakeholders involved in the cycles of production and processing seaweed up to its end-use. |
| *Business Model* | The rationale behind how an organization creates value or the *purpose* of a business (Lüdeke-Freund et al., 2016). |
| *Business Model Canvas* | A tool to design the logic behind a business value proposition by focusing on nine key components ( Osterwalder and Pigneur, 2010). |
| *Sustainable Business Model* | The creation of a business model that is driven by ecological and social aims in an economically feasible way (Lüdeke-Freund et al., 2016). |
| *Social Responsibility* | The ethical and transparent behaviour of an organization or supply chain partners regarding its commitment to society and the environment (ISO 26000, 2010; Spence and Bourlakis, 2009). |

## 2. Material and methods

A modified Business Model Canvas (BMC) (see Osterwalder and Pigneur, 2010) was used as a tool to identify the key characteristics of seaweed farms as business enterprises, and the identification of responsibility aspects. Previous research in aquaculture suggests that BMC is very well suited to characterize new aquacultural entrepreneurial activities (Pornparnomchai and Rajchamaha, 2021; Kaminski et al., 2020). However, it has not been applied to contexts outside Asia or to seaweed businesses yet. Furthermore, the inclusion of socio-ecological dimensions aimed to address the social responsibility of enterprises in being accountable for human as well as environmental aspects in the creation of a business value aligned to its supply chain (Lüdeke-Freund et al., 2016; Spence and Bourlakis, 2009). Considering the foregoing and following Daou et al. (2020), Lüdeke-Freund et al. (2016) and Osterwalder and Pigneur (2010), the data collection and analysis comprised eleven categories related to a SBM: value proposition, partnerships, relationships, activities, resources, cost structure, revenue stream, channels, customer segment, social and ecological dimensions (Appendix A). This research had the approval of the University College Dublin, Research Ethics Committee (approval number: LS-E-21-84).

### 2.1. Data collection

The data collection followed a triangulation method to assist the convergence and completeness of the qualitative data gathered, increasing the rigour and validity of the research process (Rapley and Rees, 2018; Nightingale, 2009). It comprised primary data from semi-structured interviews with seaweed growers or seaweed processors representatives ($n = 12$), complemented by participants' observation of seaweed farming operations ($n = 5$) and secondary data from official documents ($n = 37$). The seaweed aquacultural sites in Ireland corresponded at the time of analysis to 12 licenced holders and an area of approximately 250 ha not yet fully operational. Official numbers estimate that the amount of aquacultured seaweed in 2019 was about 42 t (wet) (Vazquez Calderon and Sanchez Lopez, 2022). A total of 12 seaweed companies agreed to participate (9 aquaculture-based and 3 wild-harvesting-based), all having more than 10 years of experience in the seaweed industry. The interviews were conducted either in person, by telephone or by video call between July and November 2021, securing the anonymity of the correspondents. For participants' observation, the first author took part in five major operations along the life cycle of the kelp species *Alaria esculenta* (Fig. 1) and the observations were aggregated in field notes, describing procedures related to the planning and operations at the farm level. Finally, the document analysis comprised twenty years (2001−2021) of information based on government strategies and reporting, selected and screened based on the inclusion of the keyword 'seaweed' or 'algae'.

### 2.2. Data analysis

The data analysis followed Clarke and Braun (2017) for thematic analysis using the data management software QSRNvivo 12 and excel. The data was initially coded within the eleven components as categories entailing the SBM. This followed several rounds of coding within the categories until the convergence of the main themes, which were finally combined by similarity to ensure a systematic and consistent assessment of the themes and sub-themes identified as displayed in Table 2. The main results are discussed in Section 4, supported by the scientific literature and with implications in terms of responsibility for the sustainable development of this sector.

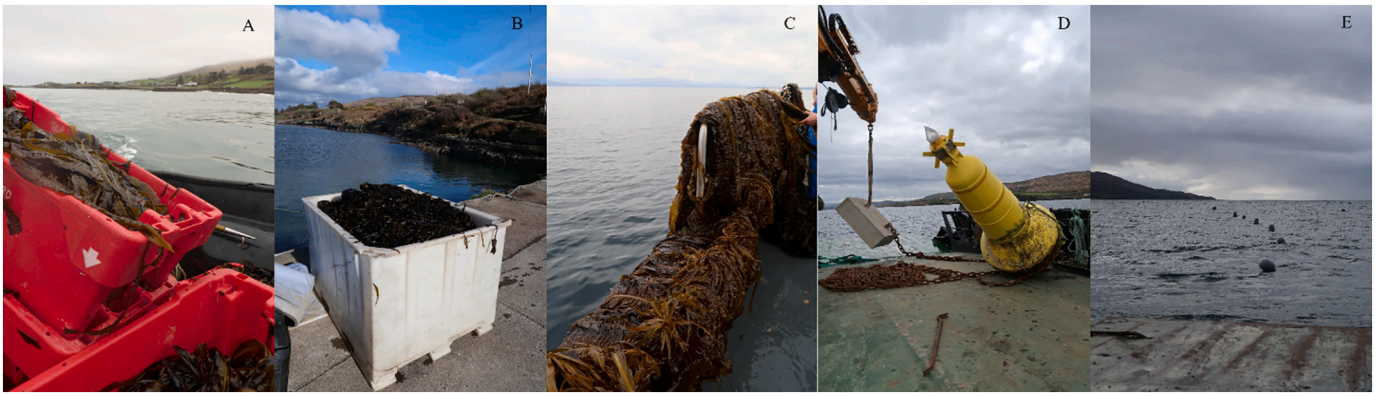


**Fig. 1.** Operations observed in 6 ha licenced cultivation site owned by Bantry Marine Research Station Ltd. (BMRS) cultivating the kelp specie *Alaria esculenta* in Bantry Bay, Co. Cork, Ireland. It illustrates A – C) different harvesting days conducted in March and April because operations are depending on the weather conditions and post-harvesting processing capacity. D) Maintenance of the farm with the replacement of anchors and buoys. The metal chains from the anchors have to be replaced every 7 years due to their deterioration by being in contact with the saltwater and one of the buoys drifted away after a storm. E) Deployment of seeded strings with seaweed spores in rope lines at sea. (Photos by Mariana Cerca).

## 3. Results

In this result section, the final themes and sub-themes within each SBMs business category are presented (Table 2). The sub-sections below expose the main characteristics of seaweed farms as emerging enterprises in Ireland, associated with the prospects of upscaling seaweed aquaculture in Ireland and responsibility over social and ecological aspects.

### 3.1. Business value proposition

The general value proposition of seaweed farms as sustainable enterprises reveals that current business models are largely aiming to connect value creation to the products and services seaweed can provide to society in terms of end-uses and potential ecological benefits such as carbon sequestration and bioremediation potentials. This is illustrated by one interviewee (…) "*I'm much more interested in the cultivated seaweed from the point of view of sustainability. I think that wild harvest, you know the demands of seaweed are getting higher, inventions, and products and plastics and bioplastics and all these other things and they're like you know using seaweed as a base, but I'm not sure where they're getting the natural resources out. So I think cultivated seaweed would be better also it's a more controlled environment. You're growing in mid-water you are not harvesting from different areas so I find the product is more consistent* (C02). While this indicates an ambitions to cultivate seaweed in order to prevent the overexploitation of wild seaweed resources, the species being explored for aquaculture in Ireland do not directly align with those being wild harvested, traditionally focused on species such as *Ascophyllum nodosum*. Cultivation nevertheless provides means to secure the quantity and quality consistency of the seaweed supplied to diverse end-uses.

The creation of social value is, on the other hand, mostly connected to local settings as rural coastal communities in the generation of employment and income, as well as in the preservation of the *Gaeltacht*.[1] The main challenge is, however, to capture and deliver this value proposition to a customer segment considering the multiple end-uses and value chains seaweed could go to. This was particularly observed among the interviewees which can be illustrated by the quote "*it has a huge amount of potential, but again, I think that's a trap. I actually… I think that's one of the main challenges that seaweed has a huge amount of potential and it's very difficult to pinpoint exactly the right thing to do for the highest return on investment and I think that's actually the main challenge, to know where, what to do and how to do it*" (C03). This *choice-paralysis* further reveals trade-offs of SBMs in aligning socio-ecological values to economic ones by focusing on higher economic-value-added products that can be more profitable. The following interviewee exemplified this positioning "*the most lucrative one would be the pharmaceuticals. Perhaps the most interesting one for people would be in human consumption and increased knowledge about human consumption*" (C01). It is indicated that the selling price of cultivated seaweed is often double the price of seaweed collected from the wild. Hence, the significant initial financial investments required to set up the farm in addition to the operational costs including processing activities are the basis of economically feasible models, where the creation of value is still mostly determined by economic terms.

### 3.2. Resources

The demand for a great number of resources is required to meet the business value proposition. The most challenging is the granting of an aquaculture licence and often also a foreshore licence before any activity can start (Government of Ireland, 2021b). The challenges at this stage foresee a whole picture of the business to be established as stated by one interviewee: "*you have to provide a full business plan in that license application, of your projections, how much you're going to produce, what is the money you're going to get for it, whether you're going to sell… How do you know that all beforehand?*" (C07). Moreover, human and financial resources are needed for the licensing application, which is reported to be a hurdle for many applicants *"(…) the licence is the issue and if you have to hire a consultancy to do environmental impact and all that kind of stuff, you know, it's too much money, it's too much time. Nobody has so much time in their hands, I certainly don't, and I've had a few businesses*" (P01). The long process of licensing reported by the seaweed growers indicates that even if interested, other stakeholders from the marine sector would not have the time or resources. So even though physical and financial aspects account for most resources needed, those are dependent on getting a formal licence which is therefore the first fundamental immaterial resource to even apply for financing such as government grants.

### 3.3. Activities

Among the main activities, the main bottleneck involves the licensing process reported above, as well as the lack of processing capacity after harvesting, currently mostly dependent on drying facilities.

[1] The Gaeltacht refers to the areas in Ireland where the Irish language (Gaeilge) is still spoken by the majority of the community and recognized by legislation for it's cultural value and heritage (Údarás na Gaeltachta, 2022). Since 1 January 2022 Irish is one of the official languages of the European Union (European Commission, 2022b).

**Table 2**
The business rationale behind emerging seaweed farms and responsibilities over ecosystems and society identified in Ireland.

| Themes in sustainable business models for responsible seaweed supply chains | |
|---|---|
| **Business Value Proposition** | |
| End-uses: Final products | Nutritious food |
| | Human and animal health: food, feed, pharmaceuticals, nutraceuticals, cosmetics and wellness |
| | Enhanced agricultural production: natural fertilisers and plant biostimulants |
| End-uses: Bio-resource supply | Consistent quality and quantity |
| Ecological | Carbon sequestration |
| | Water filtration |
| | New habitats |
| | Avoid over-exploitation of wild seaweed resources |
| Social | Employment in rural coastal areas |
| **Resources** | |
| Financial | Initial investments and operational costs |
| Physical | Hatchery or seed supply, farm set up, building facilities, seawater, electricity, transport and machinery, pier access, transport means and infrastructure |
| Human | Labour, skills and training |
| Intellectual | Granted licenses, knowledge, certifications |
| **Activities** | |
| Site selection | Land or sea site requirements for cultivation |
| Species selection | Depending on end-uses and customer segments |
| Licensing | Aquaculture licence and foreshore licence if necessary |
| Hatchery or seed supply | Set up a hatchery or find a seed supplier |
| Financing | Secure funds, private investments, or public grants |
| Innovation | Experimentation through research and learning-by-doing |
| Cultivation system | Polyculture or Integrated multitrophic aquaculture (IMTA) |
| Operations and maintenance | Optimal timing and weather conditions |
| Post-harvesting processing | Drying, ensiling, fermenting or direct extraction |
| Regulations and standards | Uncertain and dependent on quality requirements and end-uses |
| Find a customer segment | Cooperation, integration, niche markets |
| **Channels** | |
| Informal and variable | Segmented or unestablished |
| **Customer Segments** | |
| Food and food products | Fresh or dried: sea vegetable or food industry applications |
| Feed and agriculture | Animal health, soil, and plant biostimulants |
| Cosmetics, Nutra-and Pharmaceutics | Human health and wellness |
| **Relationships and Partnerships** | |
| Government agencies and policy | Advice, technical support, training, funding |
| Education and research institutions | Research and development |
| Marine sector stakeholders | Seaweed, shellfish, finfish |
| Rural coastal communities | Residents and users of the coastal-marine space |
| **Economic Feasibility** | |
| Costs | High costs for farm set-up, hatchery or seed supply, labour, infrastructure and management, post-harvesting processing |
| Revenues | Business diversification, advanced technologies, niche markets, scale-up cultivation, vertical integration. |
| **Responsibility: Social & Ecological** | |
| The natural environment | Potentials in climate change mitigation and adaptation |
| | Bioremediation's potential to improve water quality |
| | Prevention of negative impacts on coastal and marine ecosystems |
| | Potential sea-use change and alteration in the natural landscape |
| | Energy use and waste management |
| | Risk of diseases or invasive species |
| | Carrying capacity of the bay for nutrient availability |
| Development of rural coastal communities | Employment creation and income |
| | Working conditions, safety, and social protection |
| | Training and skills |
| | Avoidance of youth rural outmigration |
| | Cultural heritage and inherited rights to wild seaweed collection |
| Engagement with local actors | Local community involvement and participation |
| | Marine sector stakeholders' collaboration and partnerships |
| | Mitigation and prevention of conflicts with residents and sea users |
| | Technology development and access |
| The consumer segment | Regulations, standards, and certification |
| | Education and awareness |
| | Human and animal health |
| | Food sources from marine ecosystems |

Because seaweed has high water content and decays very quickly, the transport and post-harvesting processing needs to occur within hours from the harvesting time. In addition to optimal weather conditions and processing capacity, this imposes a particularly challenging aspect in the cultivation of kelp species, which generates large amounts of biomass. This is illustrated by one interviewee: "*but then if the weather does not work out that period, well then you won't get another slot* (referring to the drying facility) *for another two weeks, so it's very difficult to work in the sort of relationships from the point of view that you're always working with the weather and when the seaweed is due to be harvested you have to harvest it!*" (C02). This indicated a willingness of growers to own their processing facility, although given the seasonability of seaweed it would only operate for a couple of months of the year and stated by one interviewee: "*everybody's harvesting it at the same time and there's only one or two dryers, and the last thing you want is to have dryers all over the country, only be used for a very short period of time*" (C04). Besides requirements for the cultivation site such as current, water depth, salinity, and nutrient availability, it further requires pier access and short distances between the cultivation site and the processing site: *"you probably would be bringing the raw materials 8 kilometres or 5 kilometres at most, I don't think it should be much higher than that" (C08)*. This relates to decisions such as the determination of the optimal site location, the cultivation system and the scale of the operations.

The activities vary depending on the species chosen, processing method and capacity, but there are still high levels of uncertainty regarding the final applications and commercialisation: "*there's a lot of people that are jumping on the bank and saying we've got this seaweed farm, and they get funding for 50% to set up their seaweed farm. But they haven't had much consideration to marketing*" (C04). This system characterizes several producers as wholesalers and doubtful development for new entrants regarding applications and end-uses: "*and you know, sometimes some fishermen decide maybe to try that, the seaweed farming, but then they have in one go 20 tons of wet seaweed and they don't know what to do with it*" (P03). The uncertainties regarding knowledge of processing techniques and market uptake suggest drying as the most applicable post-harvesting processing method. Besides being costly with high energy usage, it optimizes transport and distribution capacity by reducing the water content from 85% to about 10% for kelp species. This prolongs the shelf life and storability of seaweed independent of previously established final uses. In this regard, it is suggested that specie selection is a key variable

in this process of decision-making for processing and commercialisation.

The decision of what species to grow is, however, dependent on the species available at the hatchery and mature levels of seedling development in commercial applications. This places seaweed growers depend on the supply of seeds or the establishment of hatcheries, as illustrated by one interviewee: "… *the problem is the lack of hatchery. We don't have a commercial hatchery in the country and we need a commercial hatchery in the country*" (C08). The species *Alaria esculenta*, for example, requires the manipulation of spore cultures in a hatchery, providing seeded strings for deployment at sea. Because it is in the hatchery where different seeding methods are tested and developed to enhance cultivation performance, a close relationship between research and technical expertise exists. Moreover, the process of experimentation was further identified as a learning-by-doing approach. For example, the trials and start-up phase require the development of specific equipment and machinery as illustrated by one interviewee: "… *we've developed a harvester machine and again it needs more work, you know, it's good, but it's not perfect, so again, we have to make more changes to it this year* " (C03). This indicates the early-stage development of the sector and its experimental character with multiple potentials for innovation.

### 3.4. Channels and customer segments

Channels are the means through which the cultivated seaweed reaches customer segments. The topics vary greatly in this category given the still informal and variable nature of the industry. Many seaweed growers are integrated into the supply system only up to the post-harvesting processing phase, the channels for wild as well as cultivated seaweed are currently being negotiated at the same level "*if you have a new customer, they're going to ring everyone. They're not just going to ring you. So we* (referring to seaweed suppliers) *ring each other and come up with a price between us*" (C01). This reflects informal partnerships happening at the upstream levels while trying to establish channels and reach new customer segments. Besides segmented or unestablished channels, the customer segments normally called "higher-value" markets are those normally targeted by seaweed growers. The focus is on niche markets of sea vegetables, nutra-and pharmaceuticals, or cosmetics, which are reasoned by the prices paid for the seaweed. Such segments often demand higher quality standards and consistency of the biomass and are therefore willing to pay more for the cultivated seaweed. This is exemplified by the following interviewee statement "*quality requirements is important dependent on what your market wants. If you're just drying it and milling it, it would be very hard to see what was in there, wasn't 100% seaweed or was it 90% seaweed? But if you are supplying the pharmaceutical industry or the Nutraceutical industry, they may well be farmed which is much cleaner product, which might mean you might have to harvest earlier, getting lower yield but better prices*" (C04). In addition, the lack of societal awareness is often mentioned as a bottleneck, particularly to those focusing on seaweed for human consumption, as exemplified by one interviewee: "*people wanted to see what it was like because of the media… and you know, people talking about it. But they didn't know how to cook it and they've had a bad experience from it you know? Because they don't know how to cook sea vegetables*" (C05). The demand for seaweed as a raw material was reported to be high. However, the challenges faced are due to processing capacity and uncertain processing methods for the targeted end-use, aligned to unestablished channels, consumer (un) awareness or cultural barriers to seaweed consumption.

### 3.5. Relationships and partnerships

The key interactions and collaborations helping to reduce risk and uncertainty are largely represented by research institutions, including government and third-level education as well as the work of semi state agencies such as the Irish Seafood Development Agency (Bord Iascaigh Mhara - BIM) and *Údarás na Gaeltachta* providing local support and advice. Due to major uncertainties regarding commercialisation, growers indicate that future developments of the sector depend on new partnerships, as pointed out by one interviewee: "(…) *I don't know how good we are in cooperative but there's a need for some sharing of facilities*" (C04). The interactions with marine sector actors, such as the shellfish industry were identified as an opportunity for sharing marine space and facilities, as well as knowledge transfer "…*like mussels' farmers, you know? They know how to put out long lines. They have thousands of lines, so you know the knowledge is there on how to farm it, you know?*" (C01). The lack of policy coherence indicates further bottlenecks despite local efforts to develop the sector, as illustrated by one interviewee: "*I think there's more work to do on policy generally. I think we're on the seaweed industry because of it. It's a bit wishy-washy at the moment. It's not really defined enough for my liking. Uhm, some people don't like administration, or I suppose, that's the policy side of it, but I think it's fundamental to building an industry*" (C08). Moreover, it indicates a lack of integration and dedicated governance for seaweed aquaculture, as stated by the quote: "(…) *there is no policy or governance, no thinking on aquaculture. I say is a low priority for the department of agriculture. They are very much focused on dairy and then fishery; but there is no focus on aquaculture* (…) *Another problem somehow serious and it's somehow so frustrating is because of regulations. So, shellfish is under the sea fisheries agency, that is the regulatory body for the seafood side, but seaweed for some reason isn't there*" (C09). This suggests inter-links between sectors and responsibilities relevant to strategic planning and integrative decision-making.

### 3.6. Economic feasibility

Seaweed cultivation is not yet economically feasible on its own and current business models are largely based on diversification. Besides seaweed being seasonal, the investment is high along with operational costs that involve maintenance, management, labour, and seed supply in addition to processing, distribution or retail. This is illustrated by one interviewee: "*the farm setup is costly (…) but it is only one, of course, once it's in. Then, after that most of the money would go into seed production, I would say and the processing, I mean drying stuff will cost energy, energy is money*" (C07). While seaweed cultivation is currently possible through partial public grants or private investments, the encouraging financing environment is reported by one interviewee: "*very few mussels businesses were able to access 30 or 40 million, whereas seaweed farms are in that position at the moment to do that you know? (…) we're talking 10s of millions. We're not talking about pocket money, you know? It's serious money with serious companies looking to invest in this sector*" (C08). Moreover, other strategies are suggested to sustain business economically. The first one indicated relates to economies of scale, although it reaches spatial constraints and potential conflicts as illustrated by one interviewee: "… *inside Bay yeah you can scale up to 10 so…30, 40, 50 hectares sites, but there is a limit and that is because of other Bay users*" (C07). The focus on niche markets is stated by one correspondent: "*I've got a very small niche in human consumption, food. That's my niche, which is probably a top-end value*" (C05) "in the same line of thinking other interviewee stated: "(…*) if we were to do seaweed on its own without any other activities, we would actually have to take a product to the market, you know?* (C01).

In addition, business diversification with the adoption of polyculture within seaweed species or with other aquacultural production such as shellfish or IMTA systems are further suggested alternatives toward economic feasibility: "*I see the benefits of a multi-trophic system where you have fish or shellfish combined with seaweed*" (C09). The cultivation of seaweed in IMTA systems and other bioremediation purposes could possibly affect the biochemical composition of the seaweed. Thus, the suitability for determined end-uses would have to be assessed. Moreover, advanced technologies such as biorefineries are suggested as future pathways by also valorising waste streams "*what other people are talking about as well is setting up biorefineries, you know and that seems to be the future to me as well because then nothing is wasted, you know?*" (C05). Apart from speculative and uncertain pathways related to the cost structure and revenue streams, all seaweed growers interviewed

reported to be expanding their businesses with increasing support provided by public or private grants.

### 3.7. Responsibility

The socio-ecological dimensions of the SBM are connected to four main themes of responsibility, which are explained below.

The aspects related to the *natural environment* indicate potential impacts, risks, as well as positive values accounted such as carbon sequestration. The conservation and prevention of impacts on ecosystems are assisted through the licensing process by looking for the potential impacts in natural protected areas such as Natura 2000 sites, visual impacts, as well as fish stocks and marine users (Government of Ireland, 2021b). Few or no negative environmental impacts were perceived by the interviewees, although future uncertainties include the risk of diseases or pollution risk depending on the type of processing method and waste management plan. Ensuring genetic diversity in seaweed cultivation was, however, related to concerns indicated by public documents where further developments should focus on native species and avoidance of monocultures (Marine Institute, 2006b; Werner et al., 2004). The main concern by seaweed growers was often related to avoidance of the overexploitation of wild seaweed resources. In official documents, seaweed aquaculture is mainly reported for its positive aspects, particularly applied in IMTA systems as included in a report involving several stakeholders of the Irish seaweed industry: "*The general view is that whilst large scale wild harvesting of seaweed could impact negatively on the environment, seaweed farming has potential benefits for the ecosystem*" (The Oireachtas Joint Committee on the Environment, Culture and the Gaeltacht, 2015). The inter-links between seaweed cultivation and wild harvesting are particularly prominent at the level of regulations or policy and therefore crucial for any planning aiming to expand seaweed cultivation and human-environment interaction in marine or coastal areas.

The *development of rural coastal communities* relates to aspects of employment creation, labour rights, as well as skills or training and avoidance of rural outmigration. The following statement illustrates this view: "*I've always worked on coastal areas, Atlantic coastal areas, and a lot of young people are leaving those areas. I'd talk that people in the seaweed industry are to keep people on the coast*" (C04). While hand-harvesting traditions are in decline given the age range of harvesters, the availability of labour in rural coastal areas and the willingness of the younger generation to work with seaweed aquaculture are reported as challenging: "*I'm looking to employ another person and I can't because it's physical work, it's hard work, and they don't want to do that*" (C02). As well as "*…well, we're looking to hire people as it is and we're finding it difficult you know? That's the thing about it. I think yes there is an opportunity, but aquaculture it's not as popular in Ireland*" (C08). In addition to labour availability, the expansion of the sector would require a wide range of competencies, several of those reported as transferable skills and knowledge from the marine sector "*I would say that in terms of growing the seaweed and sea, good boat skills, good knowledge of the sea area and everything else can be taught*" (C04). The most demanding phase in terms of technical expertise is related to the hatchery and seed supply as well as uncertain future pathways including educational programmes and training for the sector.

The sub-themes related to the *engagement with local actors* are indicated to be still overlooked. The involvement of local communities including residents and other marine space users such as fisherfolks in the planning and operations of seaweed farms is closely related to the concept of Social Licence to Operate (SLO) highlighted by Alexander (2022) and Billing et al. (2021), where the relationships at local levels are connected to the social acceptability of the activity. Emerging conflicts on existing or trial sites were reported by seaweed growers, as an example by one interviewee: "*…unfortunately, local resistance decided to sabotage and my prototype was taken (…) there was a couple of public meetings trying to get the neighbourhood on-site to demonstrate the kind of business is something to you children, and your children's children they pretty much worked with me, but very critically, you only need one or two antagonists*" (C06). The nature of those conflicts was related to local perceptions of seaweed being 'smelly' or the use of a bay area conflicting with other activities such as the fishing industry, or the fact that aquaculture is commonly related to fish farming and precedes a bad reputation. This is exemplified by the statement: "*part of the problem with aquaculture as a sector is that its image is much damaged by the salmon farm. I know that if I talk with someone that does not know about aquaculture at all and I say, 'oh I work in an aquaculture farm' they are somehow concerned because they heard all these terrible things about salmon farm*" (C09). The different perceptions and potential conflicts indicate the relevance of engagement with local actors in decision processes beyond public consultations happening during aquaculture licence applications.

Seaweed is also portrayed as a potential nutritious food source from marine ecosystems, as an alternative to food originating from terrestrial ecosystems. Accordingly, the aspects involving the *customer segment* and also broad society are related to concerns and uncertainties of potential 'unsustainable' sources of seaweed and safety issues for the consumption and use of seaweed products. For this reason, seaweed businesses commonly seek voluntary sustainability standards (VSS) certification schemes. In food and food-related applications, for example, the public requirements for organic certification in addition to food grated certified operations is further linked to health safety issues and exemplified by one interviewee: "(….) *with food grade, you have your hands up and well… which includes heavy metals, pesticides, bacteria, logical all this kind of stuff*" (C07). While an organic label as a VSS was indicated as fundamental for any seaweed farm business to operate in Ireland, standards and regulations as thresholds for biochemical content are still highly uncertain and probably impacting future developments and market applications, as exemplified by one interviewee: "*(…) the EU regulation that is going to come out from Europe, probably in 2024 and will establish the standard that will make seaweed business almost impossible to be profitable*" (P03). It is also further highlighted that at commercialisation levels, VSS or any labelling available on the market do not provide differentiation between seaweed sourced from the wild or those from aquacultural activities.

## 4. Discussion

The findings suggest that seaweed cultivation in Ireland has been driven by a top-down process of policy aims aligned to research projects and efforts of semi state agencies. Nevertheless, the increasing demand for macroalgae aligned to potential ecosystem services provided by macroalgae aquaculture such as providing low-trophic food and attending to climate mitigation targets has further resulted in a growing number of seaweed companies and the attraction of private investments to this sector. This illustrates the dynamic and timely manner of the business environment in comparison to slower changes happening in social and institutional dimensions portrayed by the lack of regulations and dedicated governance for seaweed aquaculture, along with different local perceptions and a choice paralysis of growers regarding business strategies and upscaling potentials.

Whereas in western Europe most cultivation sites are focused on *Saccharina* spp., Ireland has differentiation concerning the successful commercial cultivation of *Alaria esculenta*. According to Afonso et al. (2021), *Alaria esculenta* is particularly suitable for applications in human consumption. Nevertheless, profitable markets are generally targeted by seaweed growers along with other speculative opportunities. An example is the case of *Asparagopsis* which has a compound acting as a methane inhibitor when applied to feed in livestock production (Torres et al., 2021). This is perceived as a market opportunity considering that the Irish agricultural sector is responsible for the largest share of national greenhouse gas (GHG) emissions at the national level (Läpple et al., 2022). It would be important, however, to reason with the ethical implications of applying scarce resources in producing seaweed for feed to maintain livestock production at a lower emissions rate, when the

same resources could be applied in seaweed production for direct applications in human consumption. This follows Muscat et al. (2021) ecological principles on biomass use and prioritisation of food first, considering that multiple seaweed species could be a source of protein and plant-based food (Aschemann-Witzel et al., 2020). Meanwhile, alternative added-value products are being investigated at downstream processing stages, for example for applications in nutraceuticals, pharmaceuticals and cosmetics (Healy et al., 2022; Zhu et al., 2021).

The results further highlight the importance of human and intellectual resources to upscale cultivation systems. However, social dimensions have been disregarded in the strategic planning of bio-based supply chains including seaweed (Cerca et al., 2022). In alignment with the results of Lähteenmäki-Uutela et al. (2021), the challenges are largely related to the need for formal regulatory frameworks, integrated and dedicated policy as well as training and awareness around seaweed uses. Moreover, gender imbalances and the actual availability of labour or aspirations of younger generations to work in remote rural coastal areas should be considered. This connects to a historical problem of outmigration in Irish rural areas (Donkersloot, 2012). Technological developments and mechanisation may enable more attractive opportunities, but it may not be directly related to economically feasible models or the creation of more jobs. In addition, the development of skills and educational curricula, including experiences of youth at early stages in the marine environment could secure the resilience of aquaculture systems and the livelihoods of rural communities in the long turn. In this context, however, there is still a need to better understand rural youth and their responses to social changes and migration (Pedersen and Gram, 2017; Farrugia, 2014), where a 'sense of place' could be a further socio-cultural service provided by coastal ecosystems (Ryfield et al., 2019).

Local perceptions of seaweed aquaculture and emerging conflicts shed light on different values among the diversity of actors involved. Although seaweed cultivation is often portrayed as an advanced type of farming which does not require arable land, freshwater or fertilisers (Yong et al., 2022) it does require other factors such as dedicated areas in land-based systems or marine space depending on the species. Particularly in cases where the cultivation of kelps occurs in Bay areas with multiple users, local beliefs and norms should be carefully considered. However, public participation currently only occurs through the formal licensing process when a period of public consultation opens and local actors can make objections (Government of Ireland, 2021b). These results align with Billing et al. (2021)'s findings and the relevance of SLO and therefore rather informal mechanisms of licensing where local relationships are major determinants of community acceptance. Moreover, considering the representation of micro and small enterprises in the seaweed industry in Ireland, social responsibility also adopts fewer formal features. Following Russo and Perrini (2010) on social responsibility in SMEs, those are more related to the building of trustworthy relationships than focused on formal mechanisms of corporate social responsibility. Pendleton et al. (2022) further suggest a new licensing process integrating seaweed harvesting and farming to increase trust and legitimacy over traditional rights in the management of conflicts and sustainable use of natural resources.

The aspects related to the livelihoods of coastal communities can, however, be easily overlooked by the customer segment, particularly in longer supply chains. In alignment with van den Burg et al. (2019), the responsible expansion of the seaweed industry does not depend on economies of scale, but on viable business models that enable nature-inclusive and socially responsible production systems delivered in ethical and just ways up to consumer markets. Hence, considerations on farm scale (Wood et al., 2017) and third-party accreditation could provide a hybrid form of governance by connecting the responsibilities of the state, markets and the local community into perspective (Vince and Haward, 2017). However, it might hinder the participation of small growers that could not finance this type of accreditation. Thus, the importance of procedural fairness (Alexander, 2022) should not be overlooked in the distribution of benefits as well as mechanisms that could enable collaboration and transparency along the supply chain.

In direct conflict to the promotion of transparency and collaboration, Blok and Lemmens (2015) argue that information asymmetries can actually be seen as market opportunities, in that it is through the confidentiality of information in the form of intellectual property that seaweed businesses seek to hold a competitive advantage. For example, the sharing of data particularly on technological developments, were dealt with confidentiality and as a potential market advantage. According to Blok and Lemmens (2015), this is because the process of innovation is risky and businesses would hold alone the responsibility for the decisions taken. Here, the support of stakeholder groups such as Non-Governmental Organisations as representatives of civil society helps to give legitimation to this innovation process. For example, the World Wildlife Fund (WWF) or The Nature Conservancy (TNC) have been openly supporting seaweed cultivation (Fletcher, 2021; The Nature Conservancy, 2021), indicating the positive impacts it could provide to society. However, power relations and (un)equal opportunities in this process of innovation should be addressed, including issues of equity and justice within the circular bioeconomy debate (Kelleher et al., 2021). Moreover, forms of polycentric and collaborative governance frameworks might be able to address and acknowledge local actors with self-organization properties taking into account context and adaptation (Schlüter et al., 2020). This could direct efforts to local engagement and integrative partnerships that are also attentive to the contextual diversity of cultivation areas in terms of ecosystems and stakeholders.

This study is not without some limitations. First, seaweed aquaculture in Ireland is in the early stages and is being developed within a complex planning environment considering traditional rights over wild seaweed resources (Pendleton et al., 2022). This aligns to further uncertainties in relation to long-term policy goals, dedicated governance frameworks, socio-ecological impacts and accessible market opportunities for Irish growers. Second, potential limitations could derive from the thematic analysis. To improve the consistency and coherence of the themes and sub-themes identified, the theoretical and conceptual grounds underpinned the research process and the handling of the data with clearly stated SBM categories. The structured methodology and triangulation of the data formed the basis of a robust research design, which revealed suitability for the in-depth investigation proposed and the generation of meaningful results.

## 5. Conclusion

With an interdisciplinary research scope, this study aimed to advance knowledge regarding the future expansion of seaweed aquaculture in Ireland from a sustainability management perspective. The findings reveal relevant insights considering the interest in seaweed cultivation, although related to multiple bottlenecks and uncertainties for the development of this sector, from operational up to institutional challenges. The prospects of upscaling seaweed cultivation should address the responsibilities of emerging enterprises, accounting for aspects related to 1) the natural environment, 2) the development of rural coastal communities, 3) the engagement with local actors and 4) the customer segment. It is further suggested that macroalgal cultivation is perceived as a more responsible way of supplying seaweed by avoiding the over-exploitation of wild seaweed resources and ensuring consistent quality and quantity in the supply of seaweed. However, emerging local conflicts indicates the relevance of integrated planning regarding local engagement and partnerships, along with the need for long-term policy strategies dedicated to seaweed aquaculture aligned to the multiple uses of coastal and marine areas. Finally, the findings contribute to a broader discussion on sustainability management in aquaculture systems and the roles of seaweed cultivation and supply within the objectives of the European Green Deal and the development of a 'circular blue bioeconomy'. These results can help to guide better decision-making of prospective growers, certification bodies and policymakers in Ireland

and beyond. It remains to be investigated the scale and impact of expansion as well as ways to increase societal awareness of seaweed cultivation and its derived products. This would demand further collaboration and a dedicated governance system able to integrate the interlinks between different sectors and stakeholders' aims from production up to consumption levels. Future research could apply the same methodology to other contexts, investigate different customer segments and societal perceptions, optimize site selection and logistics, and mechanisms that could enable just and fair processes along the whole supply chain.

## CRediT authorship contribution statement

**Mariana Cerca:** Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **Amanda Sosa:** Validation, Writing – review & editing, Supervision. **Fionnuala Murphy:** Validation, Writing – review & editing, Funding acquisition, Supervision.

## Declaration of Competing Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

## Data availability

Data will be made available on request.

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## Appendix A. Guiding questions for the thematic analysis

| Business Model Component | Guiding questions |
|---|---|
| Value Proposition | What is the unique value generated for society / the environment and/or local communities? |
| Resources | What key resources does the value proposition require (e.g., physical, intellectual, human, financial) |
| Activities | What are the key activities to meet the value proposition (e.g., any bottlenecks to overcome)? |
| Channels | What are the key channels that seaweed biomass reaches the customer segment and how they are integrated along the supply chain? |
| Partnerships | What are the key partnerships influencing the value proposition, helping to reduce risk and uncertainty or in the acquisition of resources and activities? |
| Relationships | What type of relationships are established between the stakeholders? |
| Customer Segment | What are the key customer segments and for whom the value is being created? |
| Social | What are the main social aspects that should be accounted for? |
| Ecological | What are the main ecological aspects that should be accounted for? |
| Cost | What are the key costs and where do they concentrate? |
| Revenues | What are the key income streams and possible alternative income streams? |

Note: the business model canvas building blocks (Osterwalder and Pigneur, 2010) were aligned with socio-ecological dimensions of sustainability to identify the social responsibilities over the environment and society. Based on Daou et al. (2020), Wieland (2020), Joffre et al. (2017), Lüdeke-Freund et al. (2016) and ISO 26000 (2010).

## Appendix B. Semi-structured interview guide

## Appendix C. List of documents analysed

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