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Full length article

Small-scale low-tropic ocean farming and coastal rural landscapes: Why the logistics of seaweed matter? Insights from Ireland for collaborative planning

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ABSTRACT

Kelps are part of large brown macroalgae species with a fundamental role in temperate to subpolar coastal marine ecosystems and their cultivation has been expanding as part of several efforts and countries' policies. This study explores the relevance of post-harvesting logistics planning involving marine operations of emerging seaweed-based supply chains including kelp species. In the Irish context, we explore the potential of collaboration among low-tropic ocean farming sectors regarding shared space and infrastructure in rural and remote landscapes. Based on empirical data and a novel methodological approach, a multi-method analysis was performed involving geographic information systems, mathematical modelling and qualitative content analysis. The results indicate large potential production and collaboration capacity if current licensed areas and existing infrastructure were integrated with kelp cultivation for further processing and distribution in 40 local supply hubs and 14 optimal locations for shared processing facilities. Moreover, the different transportation scenarios considered indicate that costs and greenhouse gas emissions could be minimised by reducing moisture content locally and with increased payload. Further linkages reveal uncertainties in the uses of alternative methods of preservation such as ensiling and a lack of attention to non-market values. For future valorisation in diverse commercial and non-commercial applications, seaweed farming and collaborative processing opportunities still need to be incorporated into societal discourses and futures envisioned by rural coastal communities, including the engagement of young generations in such transformation pathways.

1. Introduction

There is an increasing interest in the cultivation and use of marine macroalgae (seaweed) in Europe. It is estimated that the European demand for seaweed could increase from around 270,000–8 million tonnes (t) in 2030, although the current supply mostly relies on wild harvesting and imports from traditional cultivation areas in Asia [1]. The development and valorisation of algae bioresource have been broadly supported by the European Commission's policies such as the Green Deal, and the development of a circular blue bioeconomy, including funding calls to reorient fishers to regenerative ocean farming [2,3]. Both land and sea-based cultivation sites are starting to emerge and valorisation pathways include potential applications in food and feed products, phycocolloids (alginates, agars, and carrageenans), biostimulants, fertilisers, pharmaceuticals, nutraceuticals, cosmetics, biofuels or biomaterials such as packaging or textiles [2]. Moreover, future applications from value-added bioactive compounds have been investigated with extraction techniques enabled by biorefining technologies that could include the valorisation of by-products avoiding parts of the macroalgae from being wasted after bioactive extraction techniques are applied [4–6]. However, further expanding the cultivation and valorisation of macroalgae in European contexts relates to socioeconomic barriers and limited logistical infrastructure [2], which is further associated with the rapid deterioration of seaweed after harvest [7].

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Sea-based cultivation sites are largely represented by kelp species of the order Laminariales (Phaeophyceae) such as sugar kelp (*Saccharina latissima)* and winged kelp or Atlantic wakame (*Alaria esculenta*), which are large fast-growing species and therefore generate large amounts of biomass to be harvested and processed in a short space of time. Post-harvesting processing methods such as hot air-drying are commonly used by producers and are associated with high energy usage, high costs and limited processing capacity [8]. While traditional heat or freeze-drying techniques are used to increase shelf life and facilitate transportation [9], emerging literature has suggested that ensiling techniques could be an inexpensive and environmentally sustainable alternative where air-drying is not an option. Fermenting or ensiling is an old technique that has been used to preserve food over centuries and is a common practice in colder regions where cultivation is highly seasonal [10–12]. In the ensiling process, the seaweed is fermented under anaerobic conditions using natural or commercially added lactic acid bacteria creating a low pH environment thus inhibiting spoilage microorganisms [13]. This aims to stabilise and conserve seaweed, which can be stored for long periods [14]. Hence, future perspectives on post-harvesting options including alternative preservation methods in addition to current drying methods are essential for strategic decision-making.

Contextual settings and spatial configurations are important elements, although supply chain operations in the seaweed industry remain largely undocumented [15] and current approaches related to the development of new value chains are mostly reasoned on economies of scale and competitive market behaviour [16]. To the authors' best knowledge, no studies have been conducted on the logistics of marine macroalgae, particularly not aligned to local and regional scales with potential impacts of transportation options and multiple potential valorisation pathways. Thus, the present study aimed to explore the planning of post-harvesting operations and future valorisation pathways in the context of the Republic of Ireland. About 40% of Ireland's population lives within 5 kilometres of the coast and communities along the Atlantic west coastline have long socio-cultural traditions related to traditional knowledge and uses of wild-collected seaweed species [17, 18]. Nevertheless, it has been argued that the future of the industry further depends on farming efforts, with several successful but small-scale operational sites currently in operation and mostly based on the cultivation of kelp seaweed species such as *Alaria esculenta* [8].

The Irish Macro-Algal Cultivation Strategy 2030 expects that the approximate 50 tonnes of wet weight (ww) of seaweed species cultivated annually could increase up to 2000 tonnes by the end of 2034 [19]. Together with the Strategic Plan for Sustainable Aquaculture 2030 [20], policy commitments to the sector are strongly associated with rural development plans and a focus on multitrophic aquaculture. This can be challenging for small producers in geographically remote areas, including population loss and rural youth outmigration in the West [8, 21]. Hence, the purpose of this study is to further create awareness of the relevance of post-harvesting logistics of kelps and future valorisation pathways, particularly for small-scale producers, including collaborative options in the sharing of space and infrastructure. An example are the co-benefits presented by kelp-shellfish in low-trophic cultivation systems as non-fed low-input species such as mussels, oysters and macroalgae. Studies demonstrate that these species integration could provide low-carbon products while potentially mitigating the eutrophication of local marine ecosystems by circulating the flows of nutrients, including carbon, phosphorus and nitrogen [22,23]. Inspired by futures studies [24], we aimed to answer the following research questions:

(RQ1) What is the potential production capacity of kelps in integrated cultivation with shellfish species based on currently licensed sites?

(RQ2) Where are the optimal locations for shared processing facilities based on the current infrastructure and distribution network connecting rural areas in the coastal landscape?

(RQ3) How can the costs and greenhouse gas emissions (GHG) be minimised in the transportation of kelps to the shared processing facility location?

(RQ4) What are the future valorisation pathways envisioned by policy strategies, scientific knowledge and other stakeholder groups including macroalgae farming and alternative post-harvesting methods of conservation?

The investigation helps to uncover relevant insights for strategic planning in emerging macroalgae-based value chains, including enabling collaborative settings in terms of licensed marine areas and infrastructure available for post-harvesting operations. It further highlights trade-offs of seaweed biomass logistics bound to different transportation modes and generates relevant insights for policy and management related to the importance of integrated logistics systems. Finally, it highlights potential valorisation pathways based on market and non-market applications of cultivated kelps. While uncertainties exist, the results of the study provide novelty to inform decision-making and policy developments depending on collaborative planning efforts involving multi-actors and multi-uses of marine and coastal landscapes. The inclusion of broader stakeholder representatives beyond producers and trade partners is crucial for local transformations and towards inclusive strategies and planning that takes into account vulnerable or misrepresented groups such as smallholders, community members, and the role of youth in the foreseen changes for coastal and rural landscapes.

2. Material and methods

A multi-method approach was adopted, combining two distinctive lenses on systems thinking theories [24,25]. This aimed to provide a comprehensive view of the complexity of the planning environment and envisioned futures capturing different values of kelp farming in decision-making processes. Fig. 1 displays the methodological process, which is described in detail in the following sections.

2.1. Post-harvesting planning

2.1.1. Data Collection

Spatial data from Ireland's Marine Atlas [26] was used to locate existing licenced areas as well as ports, harbour and pier infrastructure. Publicly available data on shellfish processors were retrieved from Ireland's Seafood Development Agency *Bord Iascaigh Mhara* (BIM) [27]. The data for population distribution were retrieved from the Central Statistics Office (CSO) [28], which classifies rural areas as having a population of fewer than 1500 persons. For the logistics scenarios analysed in the study case, empirical data from Bantry Marine Research Station Ltd. (BMRS) was gathered, as well as secondary data in further calculations on transportation costs and emissions.

2.1.2. Data analysis

For the spatial analysis and identification of potential supply hubs along with shared processing facilities, the data was analysed using Geographical Information System (GIS) employing ESRI® ArcGIS. The criteria for a local supply hub allocation were based on the selection of the nearest infrastructure (pier, port, harbour) to an aquaculture-licensed area for the cultivation of macroalgae and/or shellfish in rural coastal areas. Then, a transportation network analysis was performed using the extension network analyst in ArcGIS through a location–allocation model [29] to identify feasible regional processing facility locations. The allocation of 14 regional processing facilities assumed that at least two plants could be allocated per region with sea access based on the nomenclature of territorial units for statistics (NUTS) 3 classification [30]. These optimal locations aimed to represent areas with low urban influence and existing local infrastructure relevant to post-harvesting operations with opportunities for collaboration to unload kelps and potentially share processing plants.

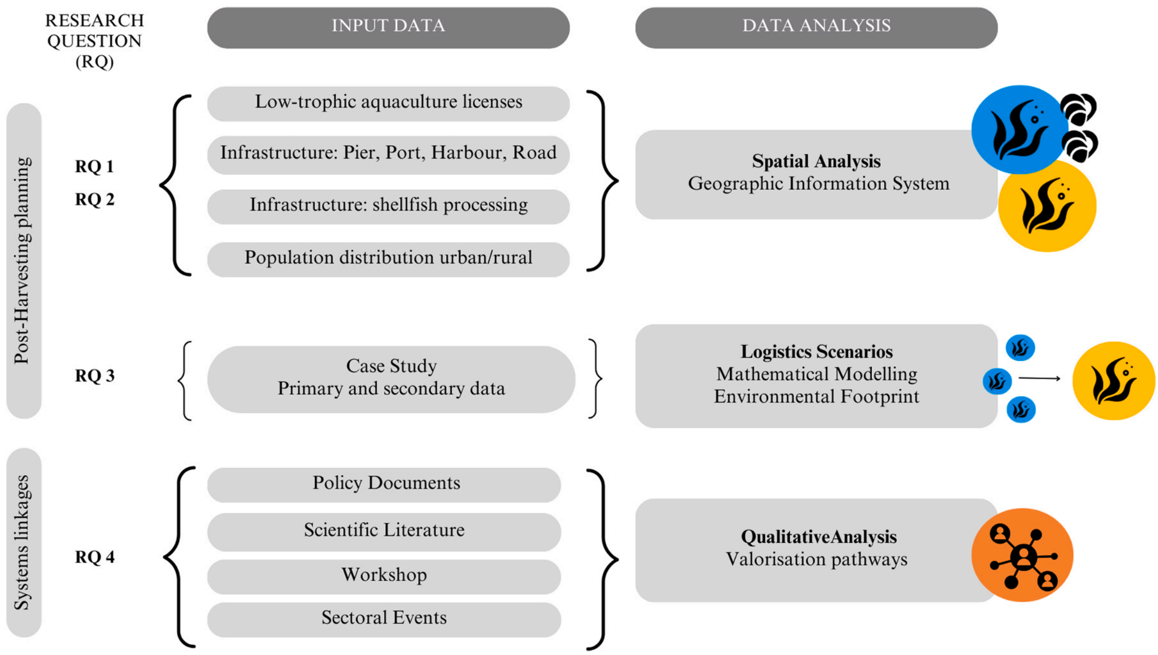

Fig. 1. Research design and methodology.

For the logistics scenarios, a case study based on BMRS was performed. Although minimal distances should be considered to minimise the impacts of transportation, shared processing alternatives at regional scales could be particularly beneficial for smallholders considering the seasonality of seaweed harvesting. Hence, the scenarios comprise of after-harvest kelp being transported (Fig. 2) *wet* either by i) trailer, ii) truck or iii) boat to be processed in the regional facility OR seaweed is transported *ensiled* by iv) trailer, v) truck or vi) boat. A linear programming model was adopted aimed at minimising the cost of transporting tonnes of wet kelp (X) from each supply hub (i) to each processing plant (j) (Min = CXij) while considering supply and demand constraints. To assess the environmental footprint, the Global Warming Potential (GWP) in terms of greenhouse gas (GHG) emissions (measured in tonnes CO2-eq) was modelled using SimaPro software [31]. GWP was measured using the 2013 IPCC climate change factors with a timeframe of 20 years [32] and includes the entire transport life cycle i.e. the construction, operation, maintenance and end-of-life of vehicle and road infrastructures. For the trailer and truck scenarios, GHG emissions data were directly available from the Ecoinvent database [33]. For the boat scenario, GHG emissions were calculated based on marine transport emissions data [34]. Boat infrastructure was assumed based on the weight and lifetime of a 12 m aluminium fishing boat (see Appendix A for the parameters used).

2.2. *Systems linkages*

2.2.1. *Data collection*

A snowball sampling of Ireland's government agencies' websites and screened based on the inclusion of the keyword 'seaweed' or 'algae' was performed (n=40). Followed by a Scopus search for scientific articles to focus specifically on the two farmed kelp species, including keyword variations of "*Alaria esculenta*", "winged kelp" "*Saccharina latissima*", "sugar kelp" and "fermenting" or "ensiling". The search yielded 110 studies, screened for relevance to the keywords with a final sample of articles aimed to explore linkages related to potential valorisation pathways for kelp species using alternative methods of preservation such as ensiling (n=70). In addition, further qualitative data was collected through stakeholder representatives' events, entailing a

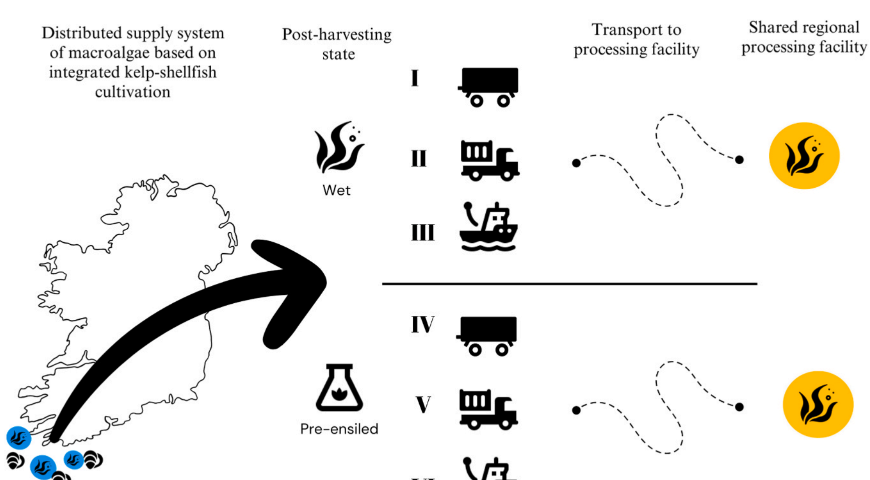

Fig. 2. Logistics scenarios to minimise post-harvesting impacts based on a study case at BMRS, Ireland.

workshop with community members (n=16) and field notes from sectoral events observed (n=2) (Full list in the supplementary material).

2.2.2. Data analysis

The sample was analysed using NVivo software and Excel for qualitative content analysis [35] using deductive coding based on [1,36,37] for market and non-market valorisation categories. The results were organised by frequency and contrasted with the envisioned views of other stakeholder representatives' including community members, sea farmers collective and environmental non-governmental organizations (NGOs) events concerning what is expected from the future embracing seaweed farming and valorisation pathways in Ireland.

3. Results

3.1. Potential production capacity and infrastructure available

There are currently 296 licensed aquaculture sites in Ireland, accounting for about 86,800 ha (ha). Approximately 98% of this area is represented by low-trophic species, largely licensed to producers of oysters or mussels, and restricted to sheltered bay areas. There are also approximately 500 piers, quays and slips infrastructure as well as nearly 80 commercial or fishing ports along the Irish coastline. Those are often very small and, in several cases located close to aquaculture sites which are linked to a great extent to highly rural or remote areas. The total potential production capacity was identified in about 40 local supply hubs based on current licensed areas from both seaweed and shellfish species (RQ1) (Fig. 3). If the total existing licenses for macroalgae would be operating, 876 t of kelps could be produced. This could increase up to 70,000 t of cultivated kelps together with existing licensed sites for

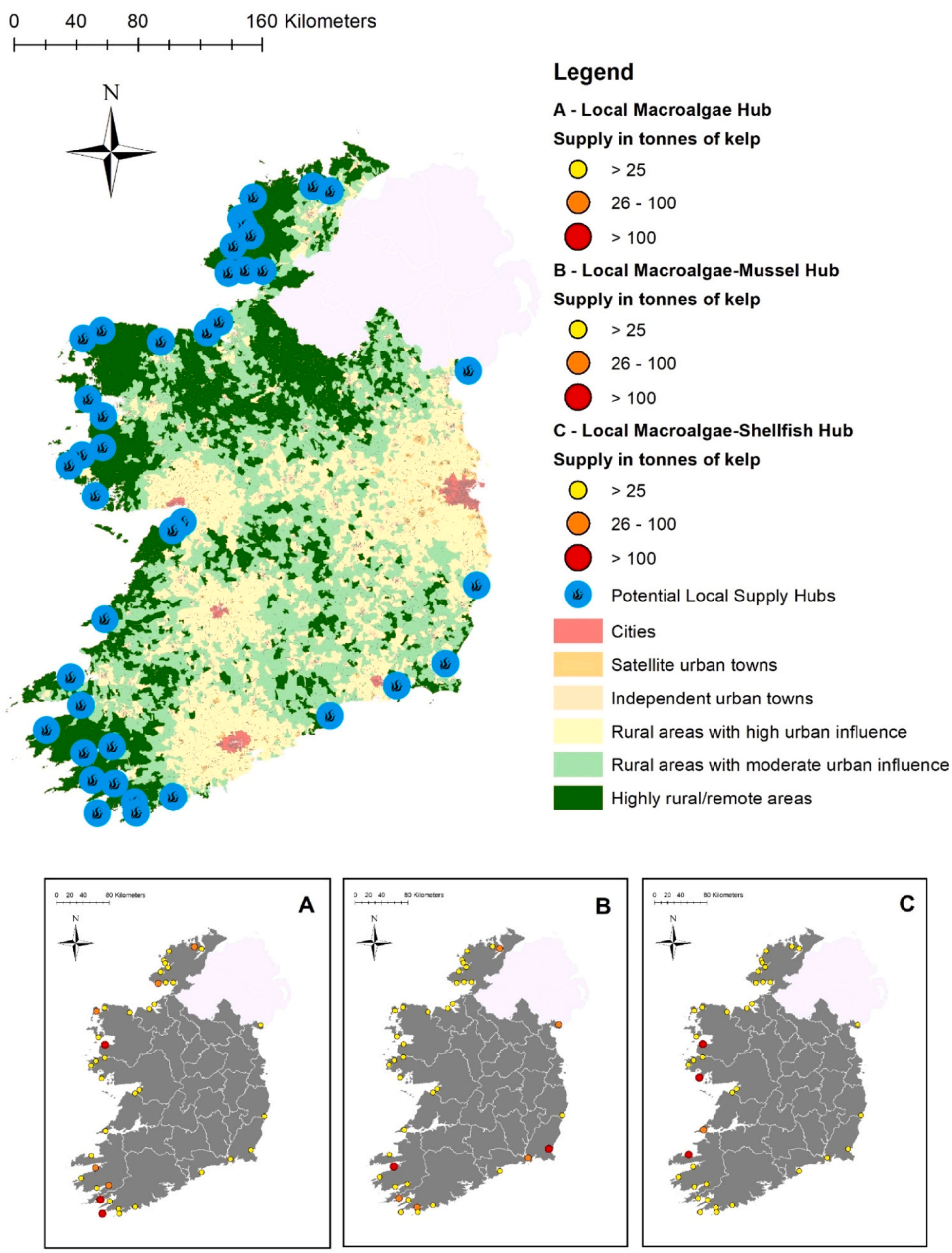

Fig. 3. Potential production volume in terms of tonnes of wet weight of the indigenous kelp species A. *esculenta* in local supply hubs identified and integrated with existing licensed areas of shellfish species.

shellfish and specifically 3800 t in the kelp-mussel integration. While this may imply that by sharing space, the production volume of shellfish could be decreased, the results also indicate that the area currently available for shellfish production is not completely operational considering that the available licensed area is much larger than what is currently being produced [38].

Emerging localities including kelp cultivation (3 A) were identified in County Donegal along Mulroy Bay and Donegal Bay, County Mayo along Clew Bay and Blacksod Bay, as well as in County Cork along Bantry Bay and Roaringwater Bay. If combined with rope mussels (3B), the supply hubs overlap with several of those identified in 3 A, indicating that location and infrastructure between mussels and macroalgae would be particularly aligned. This shifts in location points when oysters are included (3 C) due to its licensed areas being largely along Clew Bay (Mayo/Galway), Bertraghboy Bay (Galway) and Tralee Bay (Kerry). This suggests that the granting of new licensed areas and extra bureaucratic burdens on smallholders could be avoided by including native kelp species in existing licensed sites for shellfish and using the nearest infrastructure available to unload the harvested seaweed on the shore.

3.2. *Shared processing facility locations and logistics impacts*

The resulting optimal facility locations suggest shared processing plants based on the current infrastructure and distribution network in rural coastal areas in Ireland (RQ2) (Fig. 4). Their distribution is often located along the northwest, west and southwest coast, where most of the activities related to aquaculture and the fishing sectors occur (Fig. 4). The located areas are distant from major urban centres, have few opportunities in terms of local economic activities and are typically stagnant or experiencing declining population density. These locations align with plans to develop "*vibrant rural and coastal communities*" where low-trophic ocean farming can contribute to such aims also in terms of developing low-carbon value chains including shellfish and seaweed industries [20,39]. An example is the concentration of optimal shared

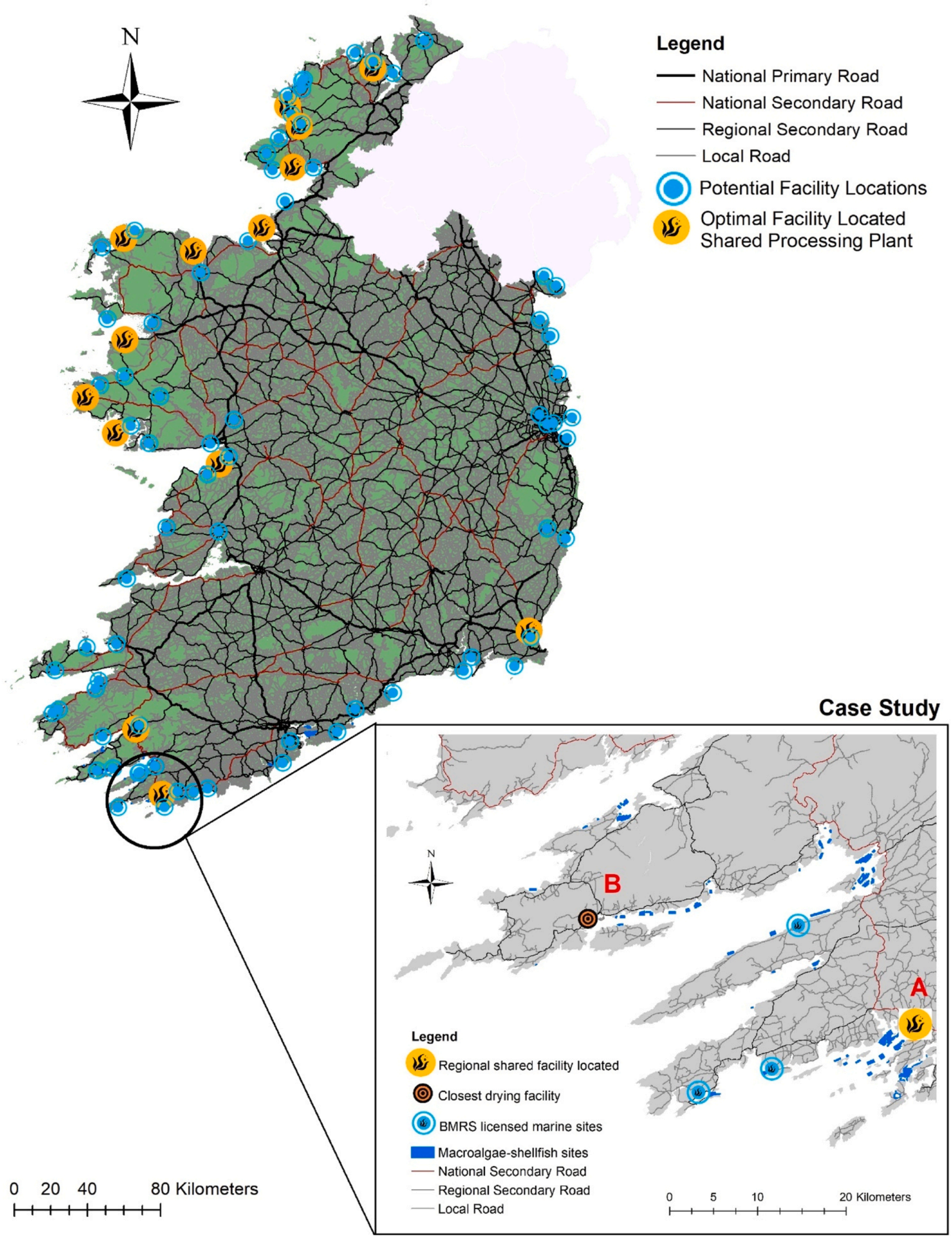

Fig. 4. Optimal locations of regional processing facilities in kelp-shellfish integration and a study case for logistics impacts in transporting kelps from local supply hubs to a regional shared plant.

processing facility locations identified in regions of the Border, represented in the country Donegal, one of Ireland's most peripheral coastal economies.

The kelps-seeded longlines are usually deployed in October and the harvested season occurs in March or April during one or different dates depending on post-harvesting processing capacity. Hence, the identified locations could assist in improving physical and social networks in terms of infrastructure available and regional collaboration for processing and distribution to reduce costs and GHG emissions in logistics planning. Fig. 4 displays the study case performed showing that the costs and GHG emissions could be minimised by using road networks with a larger truck capacity so that the payload transported is maximised, reducing the number of trips (RQ3) (Table 1). BMRS's existing licenses for three small sea sites for kelps (6, 22, and 16 ha) are not fully operational and the closest drying facility is around 60 kilometres away and has a limited processing capacity. The one with a larger capacity is about 350 km away. In a hypothetical future where a shared regional processing facility exists, the six scenarios (Fig. 2) analysed display the potential minimisation of the impacts of transportation to the processing facility as resulted in Table 1. This considers the closest existing post-harvesting processing site (plant B in Fig. 4) to the optimal shared location identified (plant A in Fig. 4).

The shared facility would significantly reduce transportation impacts as it is closer to the cultivation sites and the differences in transporting wet or pre-ensiled kelp illustrate the importance of reducing the water content. This is because the distances and moisture content are directly related to increased costs and GHG emissions, although not very significant in ensiled kelp considering that it still holds a high water content (70% against 85% wet). Moreover, the costs of transporting it by boat seem impractical, particularly by the number of trips a 5-tonne carrying capacity boat would need to make, under unstable weather conditions in the North Atlantic and between bay areas.

Table 1
Transportation costs and emissions in the logistics scenarios from a distributed small supply system from the case study at BMRS (1 = 5 t; 2 = 13 t; 3 = 18 t) with a total of 36 tonnes wet weight/annually of kelp Alaria esculenta to be regionally processed in a shared facility.

Logistics scenarios from small distribute supply system	Total number of loads *	Total costs of transportation (€)	Emissions GWP (tonnes CO2-eq)
I - Wet transported by road trailer			
Processing Facility A	11	€2090	2.25
Processing Facility B	11	€5038	5.42
II - Wet transported by road truck			
Processing Facility A	5	€ 950	1.29
Processing Facility B	5	€ 2290	3.11
III – Wet transported by boat			
Processing Facility A	8	€ 2463	5.4
Processing Facility B	8	€ 1967	4.34
IV – Ensiled transported by road trailer			
Processing Facility A	9	€1710	1.85
Processing Facility B	9	€4122	4.45
V - Ensiled transported by road truck			
Processing Facility A	4	€ 760	1.02
Processing Facility B	4	€ 1832	2.46
VI - Ensiled transported by boat			
Processing Facility A	7	€ 2155	4.7
Processing Facility B	7	€ 1721	3.78

*carrying capacity: trailer= 4 t; truck = 12 t; boat = 5 t

3.3. Valorisation potentials and future pathways

There are still large uncertainties regarding valorisation pathways for cultivated kelps, particularly on the extent future generations would be willing to engage in the algae sector and knowledge exchange within the rural coastal landscape in Ireland (RQ4). The reality of current kelp farms are niche consumer segments such as food and food ingredients by using heat-drying techniques as post-harvesting conservation methods. The results of policy aims and scientific research indicate a general alignment, although diverging at some points (Fig. 5). Scientific research including ensiling methods started strongly focusing on the potential of fermentation for biofuel production [40]. Nowadays, the use of kelps as biofuel is described as a low-value application by policy documents and encouraged through integrated biorefineries where only residues in the process of extraction should be transformed into bioethanol, biogas of biochemicals [19]. Accordingly, in more recent years scientific research has shifted the focus of end-uses of ensiling preservation methods to animal nutrition and bioactive compounds with interchangeable applications in human health nutrition, pharmaceutics and cosmetics. Ensiling methods of conservation still need comprehensive research, particularly concerning biochemical alterations during the process of fermentation which could affect the envisioned valorisation pathways for the food industry, for example [41]. Meanwhile, non-market-related valorisation including ecosystem services such as bioremediation and enhancement of marine biodiversity receive less or no attention in comparison to opportunities including blue carbon.

Concerning future pathways envisioned by other stakeholder groups, a cross-cutting aspect among civil society, sea farmers and local community representatives were the concerns regarding the future of youth in rural coastal communities in Ireland, as illustrated by one workshop participant "(…) *they* (rural communities) *should be healthy places to live and work, not just live. There needs to be employment provided to live in these rural communities and not just sleepers' zones. Everything about it is that a lot of rural communities, whole communities feel like what they're doing is breeding children for exports*" (Workshop participant). Similarly, the following statement illustrates these challenges as envisioned futures for coastal and marine areas: "*I think we need to look at the uses of the ocean openly and look at what kind of future we want (…) and I think the younger generations might be more excited about looking to these futures and alternative lifestyles and jobs that have the tourism, energy and these other benefits"* (panellist's perspective). This aligns with an upcoming bill to expand marine protected areas, highly endorsed by NGO representatives [42,43]. Moreover, policy documents often highlight tourism and recreational aspects related to coastal areas in Ireland, which further indicates the multiple values of rural coastal landscapes and the importance of biodiversity as "*a potential resource for biodiscovery and marine eco-tourism, and to conserve Ireland's marine heritage for future generations*" [44].

Despite explicit challenges in generation renewal and labour shortage within the aquaculture sector, the interest in integrating kelp and shellfish was further expressed by sea farmers' representatives: "(…) *there all these different models, especially in Maine, in the United States, that pairs oyster farming with rope mussels, and they're now growing kelp in this three-dimensional ocean farming. Systems like that sound great and we haven't had many trials of it in Ireland yet*" (participant's statement). This illustrates the potential willingness to diversify but also a demand for knowledge exchange and training. Besides the overall agreement on the importance of creating more sustainable pathways for the future of rural coastal landscapes, seaweed farming was rarely included as part of the main agenda or actions aimed for the future at the stakeholder's events observed or at the moderated workshop. This is an important finding regarding the need for social engagement beyond sea farmers, trade

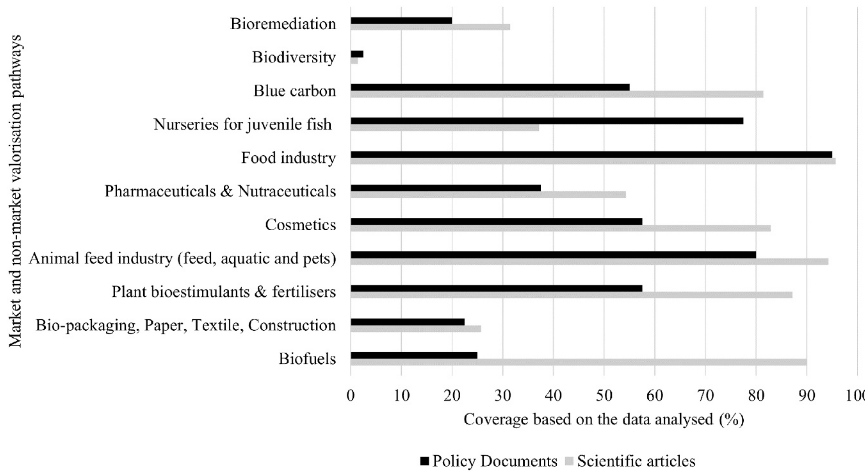

Fig. 5. Potential valorisation pathways for cultivated kelps according to policy strategies for the marine sector (dark) and scientific literature related to ensiling or fermenting applications for kelps (grey).

partners or research institutions committed to the sustainable development of the seaweed industry, as it is yet to be included in ambitious collaborative targets and the imaginaries of coastal rural communities in Ireland.

4. Discussion

Based on the findings, the total potential production capacity in terms of the volume of seaweed cultivated could exceed the 2000 tonnes targeted by government plans by 2030, if integrated production strategies with other low-trophic marine species would be pursued in Ireland. Considering that kelp and rope mussel systems are very similar in terms of necessary infrastructure, this study further adds to previous stidies [45–47] and additional results in terms of licensed areas and shared infrastructure including post-harvesting operations. Nevertheless, the consequences of climate change such as heat stress could affect the cultivated volume expected by 2030 in addition to other factors directly influencing the predicted production capacity. For example, the capacity of hatcheries in the supply of seedlings, the levels of collaboration among producers in the use and share of infrastructure as well as the granting of social license to operate. The latter relates to previous studies suggesting that large-scale seaweed farms might increase conflicts and power imbalances, often benefiting rather larger companies than effectively contributing to the livelihoods of local populations [48,49]. Local opposition related to the visual impacts of sea-based farms cannot be excluded in small-scale operations, particularly in bay areas with increased tourism activities, as an example of the southwest Coast. Nevertheless, efforts to build partnerships between tourism and the Irish seafood sector as an example of *Taste the Atlantic* programmes can be also expanded to kelp experiences in the future.

The results provide relevant information regarding the identification of potential development areas with the identification supply hubs near cultivation sites and shared processing facility locations based on existing infrastructure, functioning as a connection between marine and land-based activities. In alignment with previous analysis [50], assessing regional' infrastructure is crucial considering that many marine communities in Ireland are located far from urban areas and have less infrastructure available. Likewise, there is a significant lack of suitable port infrastructure available to be able to deliver more sustainable initiatives under the Government's Climate Action Plans, as an example of the installation of offshore wind farms [51]. This indicates that substantial investments not only in low-trophic ocean farms are necessary, but also in improving local and regional infrastructure in coastal rural landscapes for the development of the seaweed industry. Ideally, a processing facility would exist directly where the kelps are landed (pier or ports). However, due to its seasonality, it is unlikely that on-site processing would occur for small volumes. Therefore, collaborative arrangements could be envisioned as more feasible solutions in finding the *nearest-possible* facility location with a suitable capacity to process the kelps sourced from local supply hubs.

Considering the predominance of small-scale aquacultural activities and community-led coastal management approaches in Ireland [52,53] small, distributed supply systems are more likely to occur as explored by the logistics scenarios analysed. It is remarkable, however, that despite maritime shipping being considered one of the most environmentally and economically sustainable forms of transportation [54], short-sea shipping seems impractical in the case analysed. This is because most studies are applied to large-scale vessels, whereas the majority of the boats in Ireland or the EU fleet are no more than 10 m in length [55,56]. This means that inclusive logistics planning should also embrace elements of social justice and equity [57] with consideration towards smallholders' operations capacity to ensure fairer and equitable treatment of small-scale ocean farmers and enterprises. Moreover, sea transportation could have socially positive impacts by reducing local road traffic and if alternative non-fossil-based fuels are available in the future, emissions could be lowered in sea shipping as well. By thinking of new forms of social organisation and synergies between local stakeholders in the production, transport and processing of kelps, the impacts of post-harvesting could be minimised. This could be reached through cooperative models, associations of producers or not-for-profit organisations. An example is the community-led Câr-y-Môr initiative in Wales, which cultivates kelps and processes a variety of products, including food and fertilisers [58]. Although a previous study attempted to access the potential of developing community-led seaweed farming in Ireland in the community of Ardara in County Donegal Ireland, the results demonstrate scepticism towards partnerships with private sector actors regarding the distribution of profits with the local community [59]. Hence, alternative business models could be envisioned for the future towards integrative solutions at local and regional scales with direct benefits to coastal livelihoods.

This study also shed light on further linkages related to multiple valorisation pathways envisioned for kelps including market and non-market applications, as well as alternative conservation methods such as ensiling options. Nevertheless, better mechanisms to valorise the ecosystem services provided by seaweed, mussels and oysters are also needed [23]. In alignment with previous studies on blue carbon opportunities [60], there are still large uncertainties given the variation to which GHG emissions could be reduced in post-harvesting operations. This includes not only transportation as exemplified by this study but also multiple alternatives available to process kelps into final products.

In this regard, kelps valorisation strategies could include multiple alternatives, particularly concerning the replacement of emissions-intensive food and other products [61] or various bioactive compounds that could be applied in novel functional foods and pharmaceuticals due to health benefits including antioxidant and anti-hypertensive properties [62,63].

The development of more sustainable industries in coastal rural areas including valorisation pathways for seaweed seems to also depend on the interests of future generations. In this regard, aquaculture systems are also connected to cultural values through a sense of place and identity, encouraging people to remain in the area [64]. This can be very relevant to the social system in the seaweed industry in Ireland, including the prevention of rural youth outmigration, preservation of the *Gaeltacht* (Irish-speaking regions) along with additional income and employment opportunities [8,65]. It must be considered, however, indications of severe gender imbalances in the workforce of the seafood sector [38], which may hinder opportunities for more inclusive and equitable futures in the development of the seaweed industry in association with the shellfish sector. This relates to previous findings on transitions from wild-caught fisheries to shellfish and seaweed aquaculture in Maine [45] and the importance of projects such as "women in blue economy" (https://winbigproject.eu/) to investigate factors that might be preventing women from entering or progressing careers in the marine sector. Hence, rather than reflecting only on job creation in rural coastal landscapes, it is important to include reflections at micro levels of social-ecological transformations [66] for the expansion of the seaweed sector. This includes collaboration and inclusive planning in the improvement of rural infrastructure and networks, addressing labour availability and rights, as well as balancing gender inequalities and including the interests of youth. Those are valuable points for long-term decision-making but also research investigating further developments and valorisation pathways for marine macroalgae intertwined with the crucial role of logistics and the futures of rural coastal communities.

5. Conclusion

The study identified potential local supply hubs of kelp production and optimal locations for regional processing facilities by sharing space and infrastructure with the shellfish sector in Ireland, associated with a case study on the impacts of different transportation scenarios. Finally, systems linkages with potential value-added applications for kelps were explored. The results highlight the importance of post-harvesting planning and that efforts regarding infrastructure and cleaner transportation are necessary to enable more sustainable sectors to thrive. More than that, it sheds light on how the synergies with low-trophic species such as mussel producers can enable other forms of social organisation given existing licensed sites as well as the local infrastructure available. Strategies towards more integrated logistics systems may be fundamental for the inclusion of small producers in this expanding industry and towards processing alternatives. This could avoid placing individual suppliers in the international bulk market and the retention of economic values for the improvement of local livelihoods. Further, on value, the linkages exploring valorisation pathways with alternative conservation methods suggest that beyond scientific knowledge, policy goals and the experience of small producers, futures including seaweed farming may not be yet part of societal discourses or imaginaries envisioned by rural marine communities in Ireland. Finally, the novel methodological approach adopted can be replicated in other contexts and emphasises the importance of interlinking different lenses in strategic decision-making considering the uncertainty and complexity involving marine planning and policy.

CRediT authorship contribution statement

Mariana Cerca: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **Amanda Sosa:** Methodology, Software, Supervision, Writing – review & editing. **Charlene Vance:** Data curation, Formal analysis, Writing – review & editing. **Priya Pollard:** Validation, Writing – review & editing. **Julie Maguire:** Validation, Writing – review & editing. **Fionnuala Murphy:** Funding acquisition, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Appendix

Parameters used for logistics scenarios

Parameters	Value
Boat (km/h)	14.816
Boat annual usage for transport (%)	1.9–2.2
Boat Capacity - (t/ww)	5
Boat dry weight (t)	11
Boat fuel (diesel kg/km)	1.5
Boat knots to km/h	1.852
Boat length (meters)	12
Boat lifetime (years)	30
Bulk container bin in kelp capacity (kg/ww)	410

(*continued on next page*)

(*continued*)

Parameters	Value
Bulk container bin volume (m3)	1.296
Cost diesel €/litre	1.5
Density diesel kg/litre	0.87
Moisture content (ensiled) %	70
Moisture content (wet weight) %	85
Trailers Payload (t)	4.0
Trailers Volume Capacity (m3)	14.0
Transport cost (diesel + forklift) Euro/km	2
Truck Payload (t)	12
Truck Maximum Volume Capacity (m3)	42.0
Yield of *Alaria esculenta* (t/ha) in long-line culture	2.4

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2024.106140.

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