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Sustainable scale-up of Irish seaweed production: Quantifying potential environmental, economic, and social impacts of wild harvesting and cultivation pathways

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ABSTRACT

Seaweed is a versatile bioresource which can be used as a source of food, feed, fertilizer, and higher-value products. Countries with extensive sea areas such as Ireland have the potential to produce significant volumes domestically, but limitations and consequences to this potential should be considered. This study aims to capture the environmental, economic, and social consequences of different pathways for scaling up Irish seaweed production using a life cycle sustainability assessment (LCSA) framework. Six pathways are considered: manual wild harvesting by foot, manual wild harvesting by boat, mechanical wild harvesting by trawler, and three longline cultivation systems. Environmental, economic, and social impacts are considered through quantifying exergy extraction (MJex), global warming potential (kg CO2-eq), minimum selling price (MSP), and improvements in human wellbeing (HP). Finally, limitations to scale-up are assessed. The results demonstrate that manual wild harvesting has a relatively low climate impact (0.03–0.04 kg CO2-eq/kg fresh seaweed), resource intensity (1.75–2.00 MJex/kg fresh seaweed), and MSP (0.10–0.12 €/kg fresh seaweed), but a low increase in wellbeing (5.01–5.45 HP/kg fresh seaweed), while mechanical wild harvesting has a worse performance than manual harvesting in every dimension (0.14 kg CO2-eq/kg fresh seaweed, 3.50 MJex/kg fresh seaweed, 0.16 €/kg fresh seaweed, 0.60 HP/kg fresh seaweed). The impacts of cultivation pathways vary significantly, but generally perform better than wild harvesting for social impacts (18.53–20.59 HP/kg fresh seaweed) and worse for environmental and economic (MSP) impacts (0.12–0.35 kg CO2-eq/kg fresh seaweed; 2.30–5.95 MJex/kg fresh seaweed; 1.05–1.80 €/kg fresh seaweed). Nonetheless, limitations to upscaling manual wild harvesting (max 8.4 % of a future production target of 900,000 t fresh seaweed) determine that both mechanical wild harvesting and cultivation pathways will be needed to achieve future targets. It is therefore important that steps be taken to optimize each of these pathways based on the overall priorities of society.

1. Introduction

Macroalgae, colloquially known as seaweed, is a versatile feedstock which can be used for food, animal feed, fertilizer [1], energy [2], and further processed into high-value extractives for several industries [3]. In 2020, the estimated worldwide production of seaweed was 36 million tonnes fresh weight (FW), with the majority of production (97 %) concentrated in Asia [4]. While European production currently makes up a small proportion (<1 %) of the global seaweed supply [5], demand for seaweed-based products is expected to increase [6]. To increase the EU's market share, the EU has proposed an action plan "Towards a Strong and Sustainable EU Algae Sector" which aims to increase the value of the European seaweed market from 840 million euro to 9 billion euro, in part by increasing European production by 30 fold from approximately 270,000 t FW to 8 million tonnes FW by 2030 [7–9].

Ireland is one of the main seaweed producers in Europe and produces an estimated 30,000 t FW per year [10]. In contrast to global seaweed production where 97 % comes from cultivation [5], like the rest of Europe, the majority of Irish seaweed is produced from wild harvesting, with cultivation providing <1 % [11]. Irish wild harvesting is an ancient practice regarded as having a high cultural heritage and has contributed to the supplemental income of many families [12]. The traditional

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method of wild harvesting in Ireland involves manual cutting by foot during low tide, baling into 2–4 t ‘climíní’, and towing by ‘currach’ (wooden row boat) to the nearest harbour [10]. More recently, the boat and rake method has been introduced (Micheal Mac Monagail, Arramara, personal communication), where seaweed is harvested on small skiffs (4 m) during high tide using a cutting rake [13]. These manual cutting methods are inherently small-scale, with one harvester cutting an average of 1–4 t of fresh seaweed per day [10]. To upscale production, mechanised harvesting systems can be introduced [14].

Throughout Europe several mechanical harvesting methods are currently used [3]. For harvesting of kelps such as *Laminaria digitata* and *Laminaria hyperborea*, a trawler implementing a rake-like device or a fishing vessel equipped with a rotating mechanical hook (‘scoubidou’) can be used [15], while for rockweeds such as *Ascophyllum nodosum,* a vacuum-sucker or paddle-wheel cutter can be used [3]. These large industrial harvesting machines can harvest up to 150 t FW per hour [16], which can potentially improve the economics of seaweed production through increased yields [17]. However, ecological concerns can arise in the scale-up of wild harvesting. Unsustainable cutting and overexploitation in some countries has historically led to the collapse of seaweed colonies, leading to substantial negative impacts on the local biodiversity [12].

Due to concerns over overexploitation from wild harvesting, there has been an interest in increasing the proportion of cultivated seaweed (also known as seaweed aquaculture or mariculture), which would not rely on natural stocks [6]. Several seaweed species grow well in the Irish climate [18] and small-scale cultivation is already underway [3]. Seaweed aquaculture has also been hailed as an opportunity to create high-skilled jobs in rural, coastal communities [17]. However, the scale-up of cultivation in Irish waters also comes with potential trade-offs. Cultivation involves several additional life cycle stages prior to harvest, including hatchery operations, deployment and maintenance of longlines [19]. This increases the economic costs compared to wild harvest [20] as well as contributing to a significant environmental impact through infrastructure demands [21]. The large investment costs associated with seaweed farm setup has been cited as a key barrier limiting the upscaling of cultivation practices, as it limits the customer market to niche, high-value applications that can afford the high price for cultivated seaweed [22].

It is clear that while there are several pathways for seaweed production, each has both positive and negative impacts associated. It is therefore essential that the sustainability of these pathways are assessed. Life cycle assessment is a well-known methodology for assessing the impacts of a product, process, or system, where environmental impacts can be quantified through environmental LCA (e-LCA), economic impacts through life cycle costing (LCC) and social impacts through social LCA (s-LCA) [23]. Life cycle assessment has indeed been used to assess the environmental sustainability of European seaweed production systems [1,2,19,21,24,25]. Economic sustainability has also been explored in several works [19,26,27]. However, these studies have only considered the impacts of seaweed cultivation, which only contributes to 0.5 % of seaweed production in Europe [5,11]. No study has yet quantified the environmental impacts of the most common method of European seaweed production: wild harvesting. Furthermore, no studies have captured the social impacts of seaweed production systems within a quantitative LCA framework. Finally, while reports have discussed the large potential for upscaling seaweed production in Europe [9], the realistic limits to upscaling Irish seaweed production have not been quantified.

To achieve the 30-fold increase in seaweed production that would be needed to achieve the EU’s 2030 targets, scale-up of seaweed production systems is necessary. This study aims to quantify and compare the environmental, economic, and social impacts of current and potential future seaweed production pathways in Ireland which could be employed to meet European production targets. The framework is a life cycle sustainability assessment (LCSA) using two innovative life cycle assessment methodologies to determine the sustainability of the system: namely, exergetic LCA for comparing resource extraction from natural systems (wild harvesting) to resource consumption within human-made systems (cultivation), and a simplified social LCA for comparing each pathway’s contribution to human well-being. This paper not only aims to determine the most sustainable pathways for upscaling Irish seaweed production based on environmental, economic, and social criteria, but also outlines a streamlined framework for holistically comparing bio-based production systems using simple determinable metrics.

2. Methodology

This study assesses multiple scale-up pathways for Irish seaweed production based on environmental, economic, and social criteria. First, the methodology used to measure the environmental, economic, and social impacts of different wild harvesting and cultivation pathways is outlined. Then, the methodology for determining the limits to upscaling is discussed.

2.1. Quantifying environmental, economic, and social impacts through life cycle assessment

To assess the impacts of the different scale-up pathways, life cycle assessment (LCA) is used. Standardized LCA methodology is considered to have 4 steps: goal and scope definition, life cycle inventory creation, life cycle impact assessment, and interpretation [28]. Thus, this work will consider environmental, economic, and social impacts under a single LCA framework. In Sections 2.1.1–2.1.3, the goals of the study will be discussed, justifying the chosen impact categories and methodologies to be used. In Section 2.1.4, the scope of the study will be defined, including the definition of the production pathways and main assumptions considered, determination of functional unit, and setting of system boundaries. In Section 2.1.5, the system modelling and life cycle inventory (inputs and outputs to the defined system) will be described. In Section 2.1.6, the calculations which convert the inventory inputs and outputs to the chosen impacts will be outlined. Finally, the results and discussion sections provide the interpretation of the LCA.

2.1.1. Goal 1: Quantifying environmental impacts

Environmental life cycle assessment concerns the environmental impacts of a product’s life cycle. Conventionally, environmental LCAs can assess two types of impacts: midpoint impacts, such as global warming potential, eutrophication, and human toxicity, or endpoint impacts, such as damage to human health and ecosystems [29]. As climate change is a large concern for human society and thus mitigation is a main driver of bioeconomy development [30], it is common for environmental LCAs to report the global warming potential (GWP) of a product. There are several methodologies for determining GWP but it is generally measured through the quantification of greenhouse gas (GHG) emissions and the conversion of these emissions to carbon dioxide-equivalents (CO2-eq), using a specified time horizon [31]. Indeed, the GWP has been reported in many LCAs found on seaweed production systems [1,2,19,21,24,32].

However, climate change is not the only issue which is relevant to society. Overexploitation of both fossil and non-fossil resources puts significant pressure on biodiversity and ecosystem health, which in turn can have large consequences on society [33]. It is therefore of interest to measure the total resource demand of a system. This can be quantified through cumulative energy demand (CED), which uses the combined energy content of resources as a measurement of total resource consumption [31]. While CED is a good proxy for determining the environmental performance of products and processes in systems which are mainly reliant on electricity and fuel use, it does not include the impact of non-energetic resources such as minerals, metals, and freshwater, which leads to an underestimation of environmental impacts for some systems [34]. To address this, the cumulative exergy demand (CExD) method was developed, where exergy can be defined as the measure of a system's available energy. However, a key limitation in the CExD method was the lack of consideration of land use [35]. The influence of land use in particular has been neglected or undervalued in LCA studies, despite having a potentially large influence on biodiversity loss and ecosystem health [36]. Thus, in 2007 the Cumulative Exergy Extraction from the Natural Environment (CEENE) method was developed, which quantifies resource use from renewable and biomass resources by considering the net primary production of land [35]. This methodology is particularly appropriate for assessing impacts of products and systems within the bioeconomy, where large land use changes can be expected [37]. The methodology was later improved by Alvarenga et al. [38] by differentiating between resources extracted from natural and human-made systems and by adding spatially-explicit characterization factors (CFs) for land resources. Additional improvements were made by Taelman et al. [39], who determined characterization factors for sea surface occupation (SSO) to quantify resource impacts from the marine environment.

This work will use exergetic analysis to quantify the total resource intensity of seaweed production pathways, using the CExD method for material and energy use and the CEENE method for land and sea surface use. Additionally, to allow for easier comparison with previous LCAs of seaweed production, this work will determine climate change impacts based on the global warming potential of each production pathway.

2.1.2. *Goal 2: quantifying economic impacts*

An economic life cycle assessment, or life cycle costing, refers to the economic viability of a project over its lifetime. First mentioned in the 1950s, LCC is one of the oldest forms of life cycle thinking and typically considers the total financial costs related to a product which are incurred on a private individual or organization [23]. In the case of a producer, the costs are related to production, and can include both capital costs such as infrastructure, boats, and facilities, and operating costs such as chemicals, electricity, boat fuel, and labour. These costs are quantified based on the functional unit of the study, which in LCA methodology is often the mass or energy value of the product [28]. Indeed, a common method for evaluating the economic viability of a seaweed production system is through calculating the total production cost per unit mass [26,32,40,41].

The unit production cost can be translated to the breakeven or minimum selling price (MSP), which is the minimum price at which a product can be sold that will not result in economic losses to the company [42]. Determining the MSP offers a way for business owners to determine at what market price seaweed harvesting is economically viable. Thus, this work will determine the economic performance of seaweed production pathways through quantification of MSP and comparison with the current market selling price. In the case of seaweed, the market is highly uncertain, and prices are subject to fluctuations related to local and global supply and demand [43]. Consequently, that different types of seaweed have different selling prices in different geographical contexts; in 2019, the average global selling price of brown seaweeds was 0.42 €/kg FW, with an average selling price of approximately 0.33 €/kg FW for cultivated *Laminaria* and *Saccharina* species (kelps) [5]. By contrast, the price of cultivated kelps in Ireland has been estimated at about 1.00–1.50 €/kg FW [11,44]. While the value of wild harvested seaweed is not reported by the FAO [45], selling prices have been reported from as low as 0.023 €/kg in Norway [46] to as high as 0.365 €/kg in France [20]. Based on import data from the Irish seaweed industry, it can be estimated that the selling price of wild harvested seaweed in Ireland is approximately 0.16 €/kg [11].

2.1.3. *Goal 3: quantifying social impacts*

Social life cycle assessment refers to the impacts of a product's life cycle on human wellbeing. Therefore, the goal of any social LCA should be to determine a product, process or system's impacts on human wellbeing. Like e-LCA, several impact categories can be assessed in s-LCA, including health and safety, discrimination, privacy, cultural heritage, fair competition, corruption, and engagement [47]. These categories are attributed to different societal groups or 'stakeholders', including workers, consumers, value chain actors, local communities and greater society [47]. While interest in social LCA is increasing, there are still many methodological challenges, particularly with regards to the acquisition of social data and in the weight of different social impact categories [48]. To address this, Weidema [49] suggested a method to streamline social footprinting through the use of global input-output data, finding that income inequality and missing governance were key factors in human wellbeing disparities between countries. This research has recently been further developed by adjusting the weight of impact categories based on subjective wellbeing research [50].

Subjective wellbeing is defined as "how people experience and evaluate their lives and specific domains and activities in their lives" [51]. The World Happiness Reports are an extensive body of research detailing the results of subjective wellbeing research conducted since 2012 through the Gallup World Polls, where each year approximately 1000 respondents per country are asked to rate their life satisfaction on the from 0 to 10, with 0 being the worst possible life and 10 being the best possible life [52]. The life satisfaction ratings (referred to as the Cantril Ladder scale) are then analysed through statistical regressions relating them to country-specific variables such as GDP per capita, healthy life expectancy, and perceptions of corruption. For analysing individual wellbeing, the ratings are correlated to variables such as income, education, employment status, partnership and health. The production of seaweed could contribute to several of these factors; seaweed production has been highlighted as a key contributor to the blue economy and circular bioeconomy, both of which aim to promote nutritional wellness, environmental sustainability and rural job creation [17,30]. This study focuses on the work-related impacts of seaweed production pathways, using income and employment to quantify changes in human wellbeing.

2.1.4. *Scope: considered pathways, functional unit, and system boundaries*

Six seaweed production pathways are considered within the scope of this study (Fig. 1):

- Wild harvesting: Manual cutting by foot (W1)
- Wild harvesting: Manual cutting by boat and rake method (W2)
- Wild harvesting: Mechanical cutting by seaweed trawler (W3)
- Cultivation system: small-size farm (C1)
- Cultivation system: medium-size farm (C2)
- Cultivation system: large-size farm (C3)

This study will only consider the production of brown seaweed species. While it is also possible for red and green seaweeds to grow naturally in Ireland [3], there is currently no commercial harvesting of green seaweeds and very limited harvesting (<1 % of all seaweed produced in Ireland) of red seaweeds [10]. There is increasing interest in cultivation of green seaweeds such as *Ulva rigida* and red seaweeds such as *Palmaria palmata*, *Chondrus crispus*, and *Asparagopsis armata* in Ireland; however, it is thus far limited to research trials [53], with at-sea deployment thus far unsuccessful and on-land production uneconomical [44]. Consequently, there is a lack of data on commercial production pathways for the wild harvesting and cultivation of red and green seaweed species in Ireland. Second, this study will only consider brown species in the categories of rockweeds and kelps, where only rockweeds are considered for manual harvesting methods (W1, W2) while only kelps are considered for mechanical wild harvesting (W3) or cultivation methods (C1, C2, C3). This is due to topographical and market considerations for seaweed harvesting as well as data availability. Rockweeds grow on rocky shores and can be harvested by foot during low tide or by boat during high tide; for this reason rockweeds are a clear choice for hand harvesting, as demonstrated by the fact that 95 % of all seaweed currently harvested in Ireland is the rockweed *Ascophyllum nodosum*

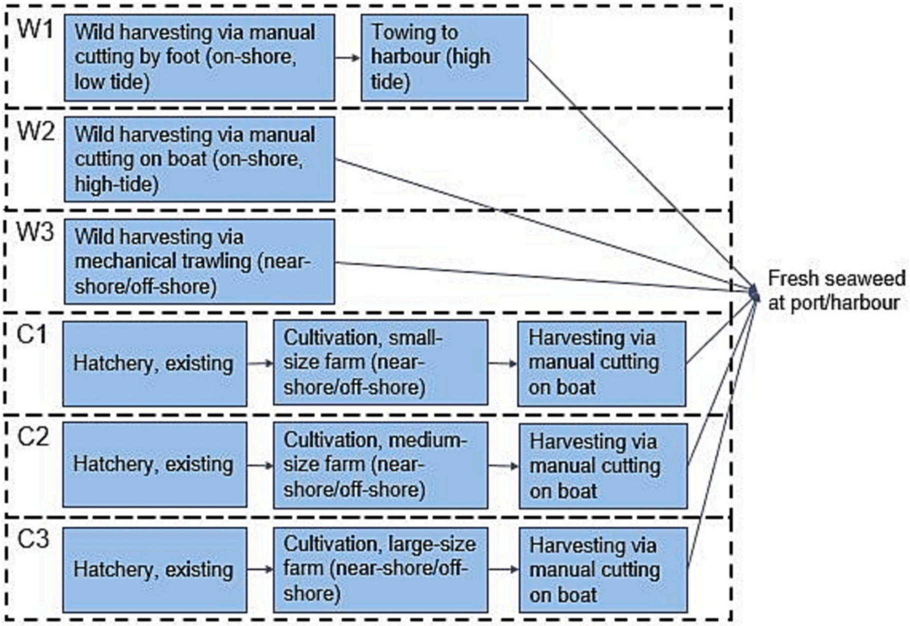


Fig. 1. Processes considered within the system boundary for each production pathway.

[10]. On the other hand, kelp grows in dense beds at depths of up to 40 m, making it difficult to access by foot [3] but more accessible through mechanical harvesting means [14]. While it is also possible to mechanically harvest rockweeds with devices such as vacuum suckers, there is a lack of data on the adoption of these methods and their impacts and thus it is not considered. Conversely, while it is possible to manually harvest Irish kelps in the form of storm cast kelp rods [10], this is a relatively small proportion (5 %) of the Irish market and, as it comprises of dead and decaying material, it has limited potential uses. Regarding cultivation, only kelps are considered as the majority of seaweed currently cultivated in Ireland are kelp species such as *Alaria esculenta*, *Laminaria digitata*, or *Saccharina latissima* [11]. It is possible to cultivate rockweeds such as *Fucus species*; however this is thus far not done in Ireland [53].

The functional unit chosen is kg seaweed fresh weight (FW) at port or harbour. As the study does not model the impacts of the use and end-of-life of the product, the LCA is cradle-to-gate. For mechanical kelp harvesting, the Norwegian-style kelp trawler is considered, as this is the most widely and successfully used method in Europe [3]. In order to easily differentiate the cultivation pathways, the three farm types are referred to as small-size (C1), medium-size (C2), and large-size (C3) based on their effective cultivation area (1.1 ha, 4.4 ha, and 17.6 ha, respectively). The classification is relative, as indeed there are theoretical concepts which consider much larger scale farms of over 1000 ha [41]. However, at present the average licensed area for cultivation in Ireland is 10 ha, with effective area being used for cultivation being typically less [53]. The sizes are therefore relevant to the Irish context. It is assumed that all cultivation sites are supplied by existing hatcheries, thus construction of the hatchery facilities is not included. The lifetime of the system is assumed to be 20 years.

2.1.5. System description and life cycle inventory modelling

Data on wild harvesting is collected from primary (Micheal Mac Monagail, Arramara, personal communication) and secondary sources [10,12,13,16,54,55]. Data for cultivation is collected from primary data from previous research [19] and from literature [24,25]. Background data is modelled in SimaPro 9.4 [56] using the Ecoinvent database [57].

2.1.5.1. Wild harvesting. In this study three wild harvesting techniques are considered: hand cutting by foot (W1), the boat and rake method (W2), and a theoretical mechanical harvesting option (W3). It is assumed that one hand harvester (W1 or W2) working 8 h a day can harvest 2 fresh tonnes of rockweeds [12]. For the kelp trawler (W3), it is assumed that 50 t/day could be harvested by a crew of three [16]. The capital equipment includes the boat purchase (skiff in W2, trawler in W3), while annually purchased equipment includes knives, rakes, and rope. Boat fuel use is calculated based on boat traveling distance and fuel efficiency (Supplementary material). The full LCI of considered equipment and energy inputs for each pathway are displayed in Tables S3-S5 (Supplementary material).

2.1.5.2. Cultivation. In this study the three cultivation pathways are modelled from independent studies on longline cultivation systems in Ireland. To appreciate the key differences in the LCI between these three studies, key material and energy input data pertaining to each is displayed in Table 1. The full LCI for the three cultivation pathways is available in Tables S6-S8 (Supplementary material).

For the small-size seaweed farm (C1), the LCI builds upon previous research done in collaboration with Bantry Marine Research Station (BMRS), which operates a seaweed hatchery and cultivation site in Bantry Bay, Co. Cork [19]. The production process begins in April, when wild samples of the seaweed species are collected locally and grown in a hatchery on-site. The 65 m2 hatchery can produce up to 100 km of seeded string per year. In the previous study it was found that 2.7 km of string was needed per year for cultivation. Thus, the equivalent hatchery area to supply C1 is 1.76 m2 per year. Deployment of the longlines occurs in October. The effective cultivation area is 1.1 ha and comprises of 11 longlines of 110 m each. According to primary data, 10 lines can be deployed in a day with 1 driver and 1 crew member. Deployment of the seeded string is done by 2 technical personnel, also at the rate of 10 lines per day. The growing period occurs from Nov-March, where maintenance on the longlines occurs once per month for the growth period. Harvesting takes place once per year in early Spring (between March–May, depending on weather conditions). The current practice is to cut the seaweed from the lines manually on a 15 m boat, which takes 3 workers and 1 driver approximately 1 h per line. The seaweed is transferred from boat to dock using plastic boxes and a forklift, which takes the workers an additional 2 h per day. Thus, the harvesting rate is assumed to be 6 lines per day.

For the medium-size seaweed farm (C2), the LCI is based off

Table 1
Main material and energy inputs per year for considered cultivation pathways.

Cultivation pathway	C1	C2	C3
Source data	Primary data	Nilsson et al. [24]	Taelman et al. [25]
Hatchery equipment and chemicals			
Total (kg)	2.18	24.20	13.32
Hatchery electricity			
Total (kWh)	483.38	911.94	2351.92
Cultivation site equipment			
Anchor blocks (concrete)	1089.00	2117.98	352.24
Mooring lines (nylon)	159.43	5.42	393.72
Longlines (nylon)	58.08	12.78	49.53
Culture string (nylon)	1.37	14.71	17.95
Shackles and chains (steel)	2.86	21.30	5546.02
Buoys (plastic)	145.20	31.36	968.65
Total (kg)	1455.94	2203.56	7328.11
Transport fuel use			
Hatchery to cultivation site (kg)	0.00	0.72	2457.31
Deployment (kg)	235.41	356.22	834.02
Maintenance (kg)	334.11	944.77	2066.00
Harvesting (kg)	57.53	287.50	416.59
Total (kg)	627.04	1589.21	5773.91

secondary data from the study by Nilsson et al. [24], which considers a seaweed cultivation site in Blacksod Bay, Co. Mayo. As the literature did not report hatchery area, it is estimated based on the amount of seeded string which would be needed for the km of longlines deployed (10.8 km). Thus, the equivalent hatchery area to supply C2 is 7.02 m2 per year. The effective cultivation area is 4.4 ha and comprises of 11 longlines of 440 m each. As in this case the longlines are 4 times the length of the small-size farm's, it is assumed to take four times as long to deploy and harvest each longline.

For the large-size seaweed farm (C3), secondary data was taken from Taelman et al. [25], which considers a hatchery in Carna, Co. Galway and a cultivation site in Ventry Harbour, Co. Kerry. The hatchery area is reported to be 120 m2 per year. The effective cultivation area is 17.6 ha and comprises of 45 longlines of 280 m each. It is assumed to take 2.5 times as long to deploy and harvest each longline compared to the small-size farm.

Longline yield, or productivity, is a significant factor in the performance of longline cultivation systems. Even considering similar cultivation methods, locations, and species, annual productivity varies widely. Average productivity for cultivating *S latissima* in Ireland is reported as 8 kg FW/m longline for the C2 farm [24] and 25 kg FW/m longline for the C3 farm [25]. Primary data from BMRS showed that productivity for *A esculenta* could vary from 6 to 18 kg/m longline, depending on the weather conditions and nearby aquaculture activities. To compare the production pathways, the productivity of all cultivation systems was adjusted to 12 kg FW/m longline.

2.1.6. *Life cycle impact assessment methods*

2.1.6.1. Environmental impacts. As mentioned in Section 2.1.1, this study uses global warming potential to evaluate the climate change impacts and exergetic analysis to evaluate the resource intensity of wild harvesting and cultivation methods for seaweed production. To calculate GWP, the International Panel on Climate Change (IPCC) 2013 100a methodology is used, which is available through the SimaPro database [31]. The methodology and equivalency factors are outlined in the IPCC 5th Assessment report [58]. Seaweed cultivation is argued as having a high potential to sequester carbon as well as nutrients in coastal waters [9]; however, unless the seaweed is actively deposited in the deep sea [40], this carbon is eventually released back into the environment at the end-of-life of the seaweed product. Thus, no CO2 sequestration is assumed.

To calculate the exergy demand, several impact assessment methods are employed. For capital equipment, chemical and material inputs, and transport-related energy use, the Cumulative Exergy Demand (CExD) method is used [34], which is available through the SimaPro database. To quantify the impacts of natural resource extraction, the CEENE method is used. In the CEENE method [38], the impact of extracting biomass resources from the natural environment can be directly attributed to the exergy content of that resource, while the impact of cultivating biomass resources within a human-made system can be attributed to the net primary production (NPP) lost by land occupation (LO):

$$\text{Impact}\left(\frac{\text{MJex}}{\text{year}}\right) = \text{CF}\left(\frac{\frac{\text{MJex}}{\text{m2}}}{\text{year}}\right)*\text{LO (m2)} \tag{1}$$

In this calculation, the characterization factor (CF) refers to the NPP in a specific location, as for example land occupation in a tropical rainforest has a different impact than land occupation in a desert [38]. A similar calculation is applied to resource extraction from the marine environment [39], where for resources extracted from human-made systems within the marine environment, impacts can be attributed to sea surface occupation (SSO). Sea surface occupation is assumed to block sunlight penetration, thus reducing NPP in that area. On the other hand, in the case of marine environments there is oftentimes only a partial blocking of the total area, which leads to the need for calculating an occupation factor, α [25]. Thus, the impact of sea surface occupation is calculated through the following equation:

$$\text{Impact}\left(\frac{\text{MJex}}{\text{year}}\right) = \text{CF}\left(\frac{\frac{\text{MJex}}{\text{m2}}}{\text{year}}\right)*\text{SSO (m2)}*\alpha \tag{2}$$

Again, a CF is applied which refers to the NPP in a specific marine location, which has been previously computed by Taelman et al. [39]. For the wild harvesting pathways, it is assumed that the impact of natural resource extraction is equal to the exergetic value of seaweed at 13.44 MJex/kg dry weight (DW), or 1.34 MJex/kg FW [25]. For the cultivation pathways, Eqs. (1) and (2) are used to determine the natural resource extraction, where the characterization factors for Ireland are 25.7 MJex/m2 for land use [38] and 22.7 MJex/m2 for sea surface use [39]. The occupation factor (α) is assumed to be 2.2 % for all cultivation methods [25]. While the cultivation pathways considered have different mooring configurations and thus their α could differ, from basic calculations it was determined that the difference would be minimal.

2.1.6.2. Economic impacts. As discussed in Section 2.1.2, this study calculates the breakeven or minimum selling price (MSP) for each pathway by quantifying all annualized costs and dividing by annual production. To calculate the MSP, the following formula can be used:

$$\text{MSP}\left(\frac{€}{\text{kg}}\right) = \left(\frac{\text{CAPEX} + \text{OPEX}}{\text{PO}}\right) \tag{3}$$

Where *CAPEX* is the total annualized capital cost, *OPEX* is the annual operating cost, and *PO* is the average annual product output [26]. CAPEX is calculated with the following equation:

$$\text{CAPEX}\left(\frac{€}{\text{year}}\right) = \frac{(\text{C} - \text{eq})*(1+\text{i})^{\text{lrp}} + \text{eq} - \text{S}}{\text{life}_{\text{project}}} \tag{4}$$

Where *C* is the total cost of capital (buildings, equipment, vehicles), *eq* is owner equity, *i* is interest on loan repayment, *lrp* is loan repayment period, *S* is the salvage value, and $life_{project}$ is the project lifetime [59]. It is assumed that the business owner has no equity and must take out a loan for the full cost of capital. The capital loan is considered to be repaid annually with an interest rate of 6 % and a loan period of 7 years [60]. It is assumed that capital equipment depreciation follows the straight-line method, i.e. the reduction in salvage value over each year is equal to the capital cost of the equipment divided by equipment lifetime. OPEX is calculated with the following equation:

$$\mathrm{OPEX}\left(\frac{€}{\mathrm{year}}\right)=exp+\mathrm{m}+\mathrm{r}+\mathrm{ins}+\mathrm{lic}+\mathrm{lab}+\mathrm{tax} \tag{5}$$

Where *exp* is material and utility expenses, *m* is maintenance of capital equipment, *r* is rental fees, *ins* is insurance fees, *lic* is license fees, *lab* is labour, and *tax* is taxes. Material and utilities expenses, maintenance, rental, insurance and license fees, and taxes are calculated based on data available from literature (Table S10, Supplementary material). Labour costs are calculated from the perspective of the business owner. In the case of self-employment or individually-owned businesses, the business income is equivalent to individual income [61]. Thus, when considering economic viability, the business owner should account for all operating costs from purchased products and services but also for their own salary. For this study, it is assumed that all wild harvesters are self-employed, and aim to earn a full-time equivalent (FTE) salary of 40,000 €/year. In the case of cultivation, it is also assumed that the hatchery and cultivation site are individually owned businesses. The hatchery scientist is assumed to be the owner of the hatchery and aims to earn an FTE salary of 55,000 €/year. The deployment site is owned by a cultivation manager, who aims to earn an FTE salary of 50,000 €/year. For all other labourers needed (towboat driver, deployment and harvesting boat driver, and additional crew members), wages are assumed based on average salaries for a given labour type [62].

2.1.6.3. Social impacts. As discussed in Section 2.1.3, this study also evaluates the contribution of seaweed production to social sustainability by determining the increase in wellbeing of the workers it employs. To calculate the relative change in wellbeing induced by the seaweed industry, it is first important to identify a baseline for the potential seaweed worker. For this study it is assumed that all workers were previously unemployed and without income. Two justifications are given for this assumption. First, a main goal of developing the bioeconomy is to develop the rural economy and create jobs [30]. While unemployment rates in Ireland have decreased significantly in the past 10 years, reaching 4.1 % (111,900 people) as of July 2023 [63], unemployment tends to disproportionally affect rural areas [64]. Second, it has long been understood that income has a logarithmic relationship with wellbeing [52]; i.e. an additional 1000 € per month has a much higher utility to someone without other income compared to someone who already makes 10,000 €/month. Thus, the income from working in the seaweed industry would contribute much more to wellbeing for otherwise unemployed people, and these individuals should be targeted to maximize the wellbeing potential of the industry.

In the World Happiness Reports, it was found that not only do income and employment have significant impacts on individual wellbeing [65], but the type of employment (e.g. full-time, part-time) impacts life satisfaction levels, and that those impacts differ regionally [66]. Based on the correlations found between individual life satisfaction and income and employment reported for 2017–2021 [52] and adjusting for different types of employment based on data from Western European countries [66], the relative change in individual wellbeing $\Delta WB_{individual}$ (measured through the Cantril ladder and hereby referred to as happiness points *HP*) which is directly related to income and employment can be represented through the following equation:

$$\Delta\mathrm{WB}_{\mathrm{individual}}\left(\frac{\mathrm{HP}}{\mathrm{worker}}\right)=0.125log(\mathrm{i})+0.478\mathrm{e}+0.497\mathrm{s}+0.544\mathrm{n}+0.304\mathrm{m} \tag{6}$$

Where *i* is the household income, *e* is full-time employed, *s* is full-time self-employed, *n* is part-time employed and not seeking more hours, *m* is part-time employed and seeking more hours, and the coefficients represent the average increase or decrease in happiness points related to those conditions. In this equation, the income variable is numerical while the employment variables are boolean (i.e. 0 for not applicable and 1 for applicable). To calculate the overall increase in wellbeing per production unit for a production pathway, the following equation is applied:

$$\mathrm{WB}_{\mathrm{total}}\left(\frac{\mathrm{HP}}{\mathrm{kg}}\right)=\Sigma(\mathrm{p}^{*}\Delta\mathrm{WB}_{\mathrm{individual}}) \tag{7}$$

Where WB_{total} is the total increase in wellbeing, *p* is the number of workers per kg FW in a given category and $\Delta WB_{individual}$ is the change in individual happiness points as calculated in Eq. (6). The income and employment status of each worker is determined through the salary and labour hours required per year for each job type. An important factor in the seaweed industry is that due to the seasonal nature of supply, most jobs are not full-time [3]. However, it is important to consider that upscaling within the seaweed industry could result in several changes to the current working conditions. First, multiple smaller-sized sites could be owned and managed by a single person; thus, for this study it is assumed that one owner can own and manage 10 small-size farms (C1), 2.5 medium-size farms (C2), or 1 large-size farm (C3). Furthermore, while currently workers on cultivation sites are typically only needed a few days per year (primary data), if there were significantly more seaweed farms in Ireland, cultivation workers could be employed at multiple farms each year. This would significantly decrease the number of separate workers needed per tonne of seaweed produced as well as increase the individual working hours and thus income per worker per year. For this study it is assumed that harvesters would be able to work for the entire harvesting season (4 months), deployment workers could be employed between October–November (2 months), and assistant cultivation scientists could work for the entire deployment and growth seasons (6 months). The number of workers for each pathway is displayed in Table S9 (Supplementary material), as well as their FTE salaries and employment status.

2.2. Determining the feasibility of upscaling Irish seaweed production to meet European targets

As previously mentioned, the European Union aims to produce 8 million tonnes FW of seaweed by 2030, corresponding to a 30-fold increase in current European production levels [7]. To meet this goal, it can be assumed that Ireland would also need to increase its current production by 30-fold, corresponding to an annual production of 900,000 t FW. There are practical barriers to scale-up which need to be considered. In the case of wild harvesting, scale-up potential is limited by the natural resource available in Ireland (ecological limit). In the case of cultivation, scale-up potential is limited by sea surface availability (spatial limit). These limitations should first be quantified and will be discussed in the following sections. Then, considering the future target of 900,000 t FW of Irish seaweed production/year, feasible scenarios for meeting this target are identified in terms of resource availability. Finally, the environmental, economic, and social impacts of these feasible scenarios are determined.

2.2.1. Assessing the ecological limits of Irish wild harvesting

For wild harvesting, the theoretical limit for seaweed production is based on the natural resource availability and the allowable exploitation rate of the resource, where the exploitation rate refers to how much of the total seaweed stock can be harvested per year without collapsing the entire seaweed colony or causing other ecological degradation [12]. the following calculation is used:

$$\mathrm{B}\left(\frac{\mathrm{tonnes\ FW}}{\mathrm{year}}\right)=\mathrm{A}\ (\mathrm{tonnes\ FW})^{*}\mathrm{E}\left(\frac{\%}{\mathrm{year}}\right) \tag{8}$$

Where *B* is the harvestable biomass, *A* is the total resource availability, and *E* is the allowable exploitation rate (% total biomass allowed to be harvested per year). The total resource availability is determined based on field sampling studies, and the exploitation rate is determined based on ecological recovery studies (Supplementary material).

2.2.2. Assessing the spatial limits of Irish cultivation

For cultivation, it is assumed that the theoretical limit for seaweed production is the licensable sea surface area of Ireland. The following equation is used:

$$\text{B}\left(\frac{\text{tonnes FW}}{\text{year}}\right) = \text{S (ha)*P}\left(\frac{\text{tonnes FW}}{\text{ha*year}}\right) \tag{9}$$

Where *B* is the harvestable biomass, *S* is the total sea surface availability, and *P* is the specific productivity for cultivated seaweed. The total sea surface availability is determined based on Ireland's unutilised sea area, and the specific productivity is determined based on longline productivity and density (Supplementary material).

3. Results

In this section, the environmental, economic, and social impacts of Irish seaweed production are presented. Section 3.1 describes the impacts from each production pathway while Section 3.2 describes the impacts of combined pathways to reach a future production target of 900,000 t FW/year.

3.1. Quantifying the environmental, economic, and social impacts of production pathways

Figs. 2 and 3 display the exergy demand and global warming potential (GWP) for the 6 production pathways considering a functional unit of 1 kg FW seaweed at harbour. For the wild harvesting pathways (W1, W2, W3), natural resource use (extraction of seaweed from the natural environment) dominates total exergy use. Despite this, manual wild harvesting methods (W1 and W2) are found to have the lowest resource intensity of all pathways (1.75–2.00 MJex/kg FW). In the case of mechanical trawling (W3), resource use increases significantly (3.50 MJex/kg FW), due to more transport fuel required to travel to and from kelp beds and for trawling itself. For the cultivation pathways (C1, C2, C3), capital equipment, chemicals, nutrients, and fresh water use as well as transport are the largest exergy users. However, the resource intensity varies significantly among cultivation pathways (2.30–5.95 MJex/kg FW), with the medium-size farm (C2) performing the best and the small-size farm (C1) performing the worst. A similar pattern can be seen for GWP, where manual wild harvesting pathways (W1 and W2) are found to have the lowest GWP (0.03–0.04 kg CO2-eq/kg FW), followed by the medium-size seaweed farm (0.12 kg CO2-eq/kg FW), mechanical wild harvesting (0.14 kg CO2-eq/kg FW), large-size seaweed farm (0.26 kg CO2-eq/kg FW), and small-size seaweed farm (0.35 kg CO2-eq/kg FW).

Figs. 4 and 5 display the minimum selling price (MSP) and potential increase in wellbeing (WB) per kg seaweed FW for the 6 production pathways. The main cost for manual wild harvesting (W1 and W2) is labour. Due to the need to hire the towing boat, the wild harvester harvesting by foot (W1) has slightly higher costs (0.12 €/kg FW) compared to the wild harvester harvesting by boat and rake (W2) (0.11 €/kg FW). Both manual harvesting pathways have a lower MSP than mechanical harvesting (W3) (0.16 €/kg FW), due to the high capital and fuel costs of the seaweed trawler. Nevertheless, all wild harvesting pathways are found to be economically viable at an estimated market selling price of €0.16/kg FW. All cultivation pathways are found to have significantly higher production costs than wild harvesting (1.05–1.80 €/kg FW), with major cost contributions from capital equipment, boat fuel, and labour. Only the medium-size farm (C2) is found to be economically viable at the current Irish market selling price of 1.00–1.50 €/kg FW, and none of the farms are competitive with the global selling price of 0.33–0.42 €/kg FW. However, as cultivation pathways are much more labour intensive than wild harvesting pathways, they contribute much more to social wellbeing. The maximum increase in wellbeing is attributed to the small-size farm (C1) (20.59 HP/kg FW) followed by the medium-size farm (C2) (19.24 HP/kg FW) and large-size farm (C3) (18.53 HP/kg FW). Of the wild harvesting pathways, harvesting by foot (W1) is found to cause the highest increase in wellbeing (5.45 HP/kg FW), with the boat and rake method (W2) having a slightly lower potential for wellbeing increase (5.01 HP/kg FW). Finally, mechanical harvesting (W3) creates the least jobs and therefore has the lowest potential for increasing wellbeing (0.60 HP/kg FW).

3.2. Determining the feasibility of upscaling Irish seaweed production to meet European targets

The total resource availability of rockweeds and kelps in Ireland is estimated at 302,024 and 1,100,753 t FW, respectively. Assuming an exploitation rate of 25 % for manual rockweed harvesting and an exploitation rate of 15 % for mechanically harvested kelp, the limits to

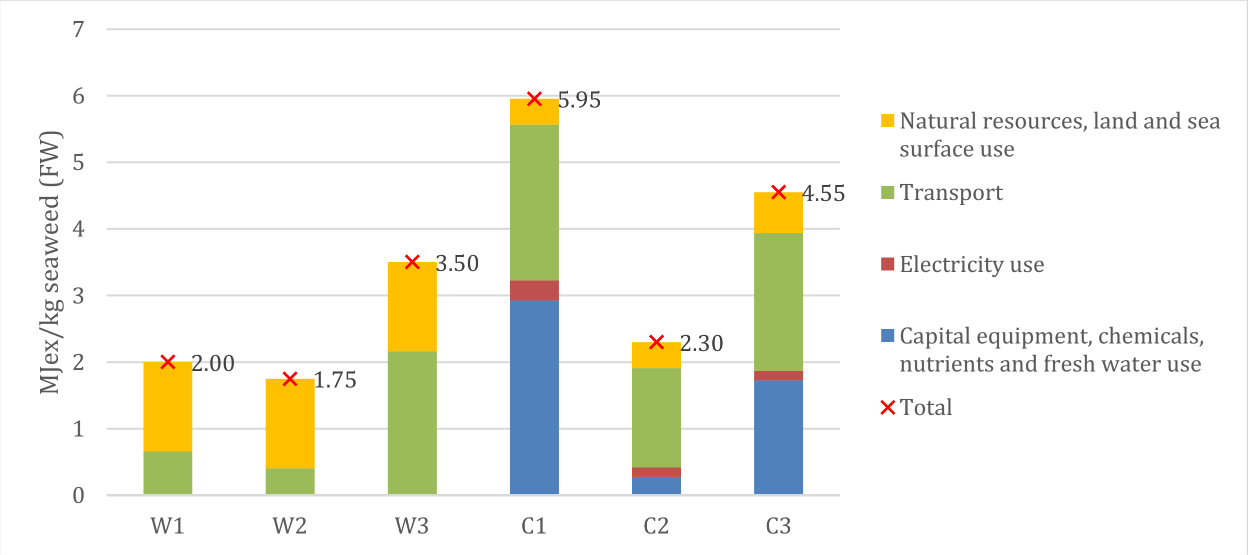


Fig. 2. Exergy demand (MJex) of production pathways considering a functional unit of kg seaweed fresh weight.

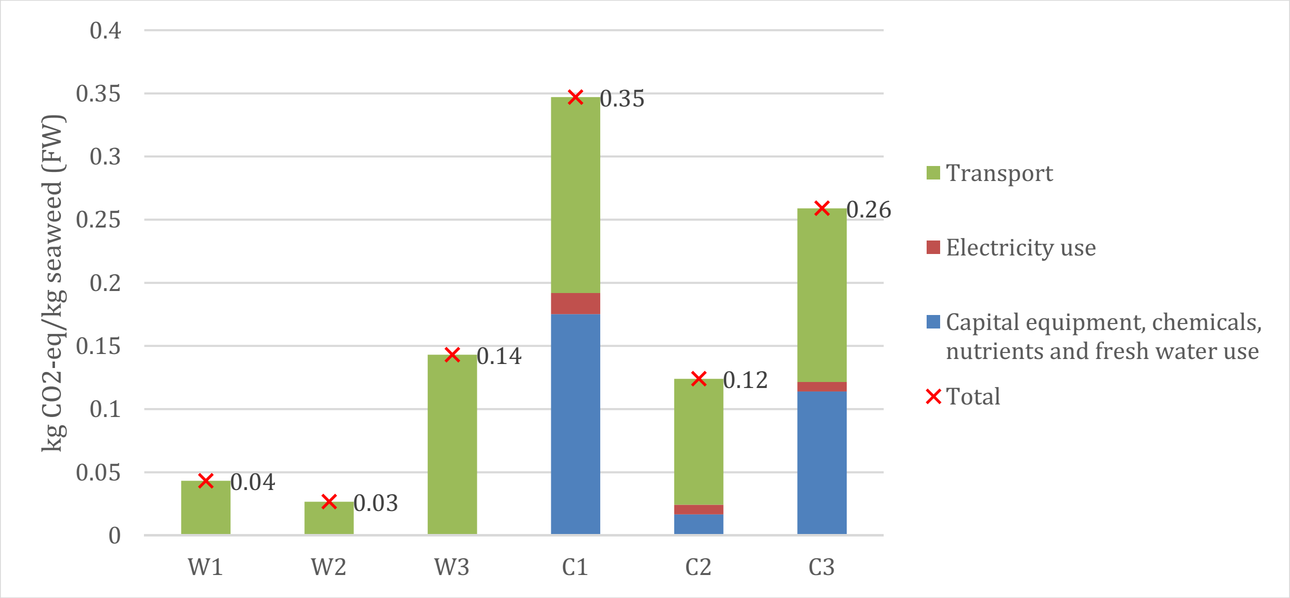


Fig. 3. Global warming potential (kg CO2-eq) of production pathways considering a functional unit of kg seaweed fresh weight.

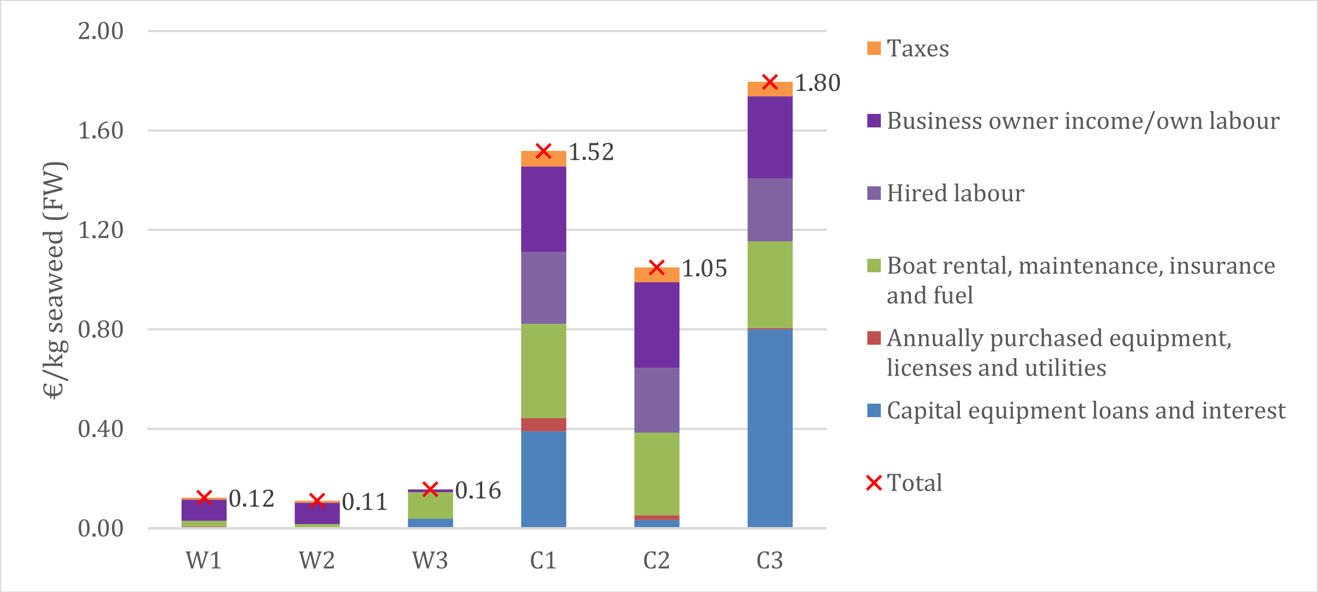


Fig. 4. Minimum selling price (€) of production pathways considering a functional unit of kg seaweed fresh weight.

Irish seaweed production from wild harvesting are 75,506 t FW/year for rockweeds and 165,113 t FW/year for kelps, resulting in a total wild harvest of 240,619 t FW. The total Irish sea surface area within 22 km of the shoreline is approximately 150,000 km2. However, it is estimated that 25 % of this area is currently being utilised for other purposes. The total available sea surface area for upscaling seaweed cultivation is therefore estimated at 112,500 km2. Based on a specific productivity of 13.2 t FW/ha/year, the limit to Irish seaweed production from cultivation is estimated at 148,500,000 t FW/year.

The estimated harvestable biomass from cultivation is well above the defined target for seaweed production of 900,000 t FW/year, meaning 100 % of future production can come from cultivation. On the other hand, no >26.74 % (240,619 t FW) of total production can sustainably come from wild harvesting. Furthermore, wild harvesting pathways are limited by the differing availability of rockweed and kelp resources in Ireland (Fig. 6). A 20 % contribution of wild harvesting to the total 900,000 t FW annual production is only possible if <42 % (75,600 t FW) of the wild harvested resource comes from rockweeds and no >92 % (165,600 t FW) comes from the harvesting of kelps. A 10 % contribution of wild harvesting to total production is only possible if no >84 % (75,600 t FW) of the wild harvested resource comes from rockweed harvesting.

Considering the limitations of wild harvesting as a % of total seaweed production and rockweeds and kelps as a % of total wild harvesting, several feasible scenarios can be defined (Table 2). As previously discussed, wild harvesting of rockweeds is conducted through manual methods (W1 or W2), while kelp beds are harvested through mechanical means (W3). Cultivated production can come from any of the cultivation pathways (C1, C2, or C3). To reduce the number of scenarios, the highest and lowest possible inclusion of kelps and rockweeds is assumed for each i.e. for 20 % contribution of wild harvesting to the total production target, harvesting of rockweeds (W1 or W2) can contribute up to 40 %

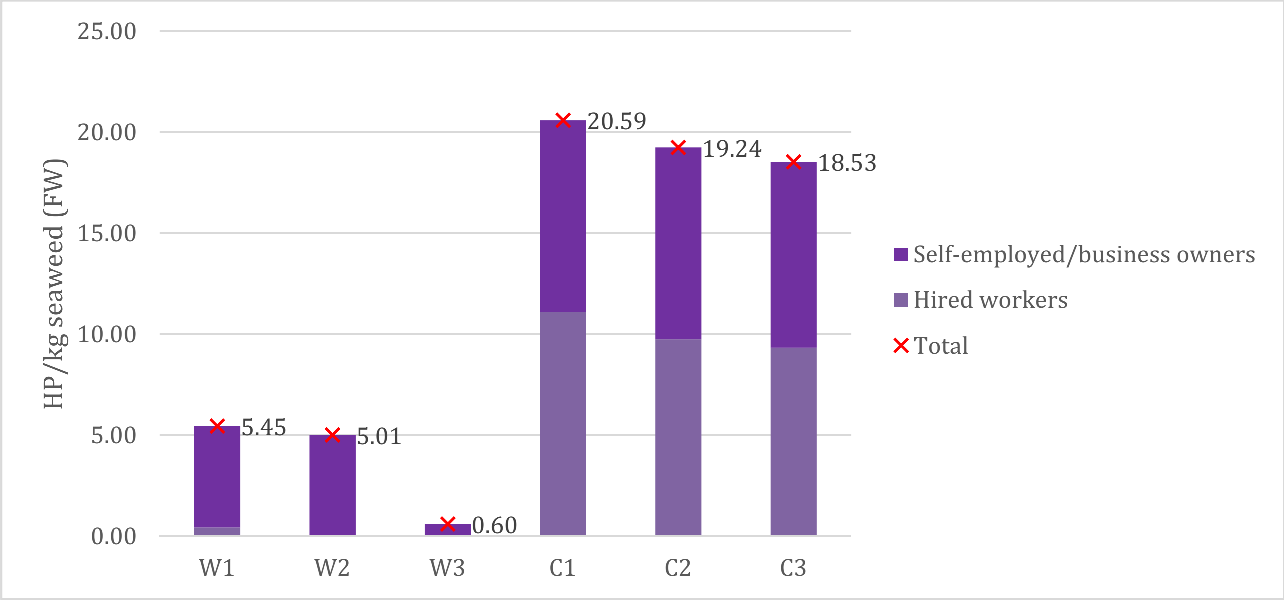
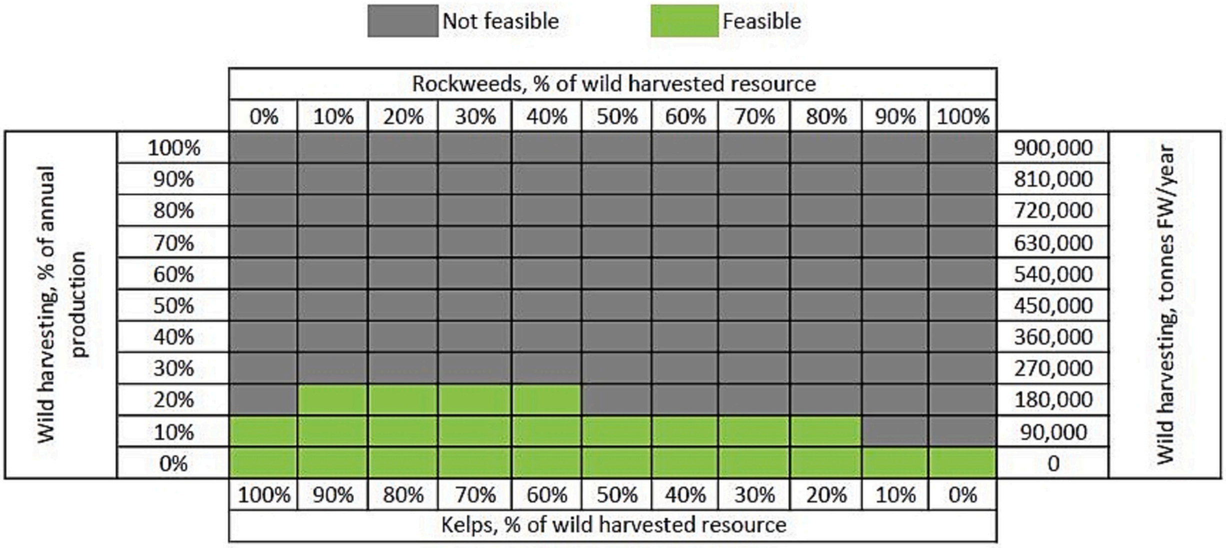


Fig. 5. Human wellbeing impacts (HP) of production pathways considering a functional unit of kg seaweed fresh weight.



⬛ Not feasible 🟩 Feasible

Wild harvesting, % of annual production	Rockweeds 0% / Kelps 100%	10% / 90%	20% / 80%	30% / 70%	40% / 60%	50% / 50%	60% / 40%	70% / 30%	80% / 20%	90% / 10%	100% / 0%	Wild harvesting, tonnes FW/year
100%	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	900,000
90%	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	810,000
80%	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	720,000
70%	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	630,000
60%	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	540,000
50%	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	450,000
40%	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	360,000
30%	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	270,000
20%	⬛	🟩	🟩	🟩	🟩	⬛	⬛	⬛	⬛	⬛	⬛	180,000
10%	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	⬛	⬛	90,000
0%	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	0

Rockweeds, % of wild harvested resource
Kelps, % of wild harvested resource

Fig. 6. Scale-up potential for Irish seaweed wild harvesting, considering % contribution of wild harvesting to total annual production target and % contribution of rockweeds and kelps to total wild harvested resource.

while harvesting of kelps, (W3) can contribute up to 90 %, with the remaining 80 % contribution being provided by cultivation from 100 % C1-type farms, 100 % C2-type farms or 100 % C3-type farms. Fig. 7 displays the environmental, economic and social impacts of the considered scenarios. The scenario with the worst environmental performance (highest exergy demand and GWP) but best social performance (highest HP) is C1, which considers scale-up with 100 % production from C1-type farms. The worst social performance is from A12, the scenario with 20 % production from wild harvesting (2 % from W2, 18 % from W3) and 80 % production from C3-type farms. Scenario B5, which considers 10 % production from wild harvesting (8 % from W2, 2 % from W3) and 90 % production from C2-type farms, has the best environmental performance. The best economic performance (lowest MSP) is from scenario A5, which has 8 % production from W2, 12 % production from W3, and the remaining 80 % production from C2-type farms. The worst economic performance is from C3, which considers 100 % production from C3-type farms.

4. Discussion

In this study, several seaweed production pathways were compared based on environmental, economic, and social impacts. Despite the direct extraction of biomass from the environment, environmental impacts of manual wild harvesting methods (W1 and W2) were found to be quite low. However, both exergy demand and global warming potential were found to be significantly higher in the mechanical wild harvesting pathway (W3) due to diesel fuel use in the trawler. Mechanization in agriculture has been shown to have negative impacts on the environment through increased greenhouse gas emissions [67], and our results confirmed that the marine environment reflects the same trend. All wild harvesting pathways were found to be economically viable, with the lowest MSP found from the boat and rake method (W2), followed by manual harvesting by foot (W1) and mechanical harvesting (W3). However, all of these pathways contributed little to social wellbeing, with harvesting by foot (W1) contributing the most, and mechanical

Table 2
Name and description of each scale-up scenario.

Scenario name	% of total production					
	W1	W2	W3	C1	C2	C3
A1	8 %	0 %	12 %	80 %	0 %	0 %
A2	8 %	0 %	12 %	0 %	80 %	0 %
A3	8 %	0 %	12 %	0 %	0 %	80 %
A4	0 %	8 %	12 %	80 %	0 %	0 %
A5	0 %	8 %	12 %	0 %	80 %	0 %
A6	0 %	8 %	12 %	0 %	0 %	80 %
A7	2 %	0 %	18 %	80 %	0 %	0 %
A8	2 %	0 %	18 %	0 %	80 %	0 %
A9	2 %	0 %	18 %	0 %	0 %	80 %
A10	0 %	2 %	18 %	80 %	0 %	0 %
A11	0 %	2 %	18 %	0 %	80 %	0 %
A12	0 %	2 %	18 %	0 %	0 %	80 %
B1	8 %	0 %	2 %	90 %	0 %	0 %
B2	8 %	0 %	2 %	0 %	90 %	0 %
B3	8 %	0 %	2 %	0 %	0 %	90 %
B4	0 %	8 %	2 %	90 %	0 %	0 %
B5	0 %	8 %	2 %	0 %	90 %	0 %
B6	0 %	8 %	2 %	0 %	0 %	90 %
B7	0 %	0 %	10 %	90 %	0 %	0 %
B8	0 %	0 %	10 %	0 %	90 %	0 %
B9	0 %	0 %	10 %	0 %	0 %	90 %
C1	0 %	0 %	0 %	100 %	0 %	0 %
C2	0 %	0 %	0 %	0 %	100 %	0 %
C3	0 %	0 %	0 %	0 %	0 %	100 %

harvesting (W3) contributing the least. Interestingly, the poorer performance of the mechanical harvesting method W3 contradicts the idea that pathways which reduce labour necessarily reduce costs overall [2,20]. While mechanical harvesting was found to reduce the costs associated with labour, it would also require the use of large, specialised boats which increases the costs associated with capital equipment and fuel. This reflects the findings of Burrows et al. [46], who discussed the difficulties of implementing economically feasible mechanical wild harvesting scenarios in Scotland.

Compared to wild harvesting methods, the cultivation pathways (C1-C3) had a much higher labour demand and as such could contribute much more to social wellbeing increases; however, cultivation pathways also had significantly higher environmental and economic impacts. Transport was found to be a significant contributor to environmental and economic impacts in cultivation. Capital equipment – particularly that used in deployment - was also a significant contributor, as well as the most variable among cultivation pathways (Table S11, Supplementary material). Generally, it was found that environmental and economic impacts decreased as the amount of deployment equipment used decreased. For instance, C2 used the least deployment equipment (0.038 kg/kg FW) and performed the best in terms of both environmental and economic impacts. However, the type of equipment used was also important; while C2 and C3 used a comparable amount of deployment equipment per functional unit (0.038 and 0.048 kg/kg FW, respectively), C3 had significantly higher impacts than C2. Regarding economic costs, C3 performed even worse than C1, despite C1 using significantly more deployment equipment (0.100 kg/kg FW). C3 was designed quite differently to C1 and C2 as it used significantly higher amounts of steel, which has a significantly higher environmental footprint and unit price (1.84 kg CO2-eq/kg and 13.59 €/kg) compared to the concrete blocks (0.16 kg CO2-eq/kg and 0.33 €/kg) used by C1 and C2. These insights reveal the large impact of farm design on both environmental and economic impacts of seaweed cultivation. Indeed, some studies on seaweed cultivation [1,25], and other offshore applications such as wind and wave energy farms [68,69], have indicated that there is a large potential to reduce environmental and economic impacts by optimising the location, configuration, and design of offshore installations. It is therefore suggested that future cultivation

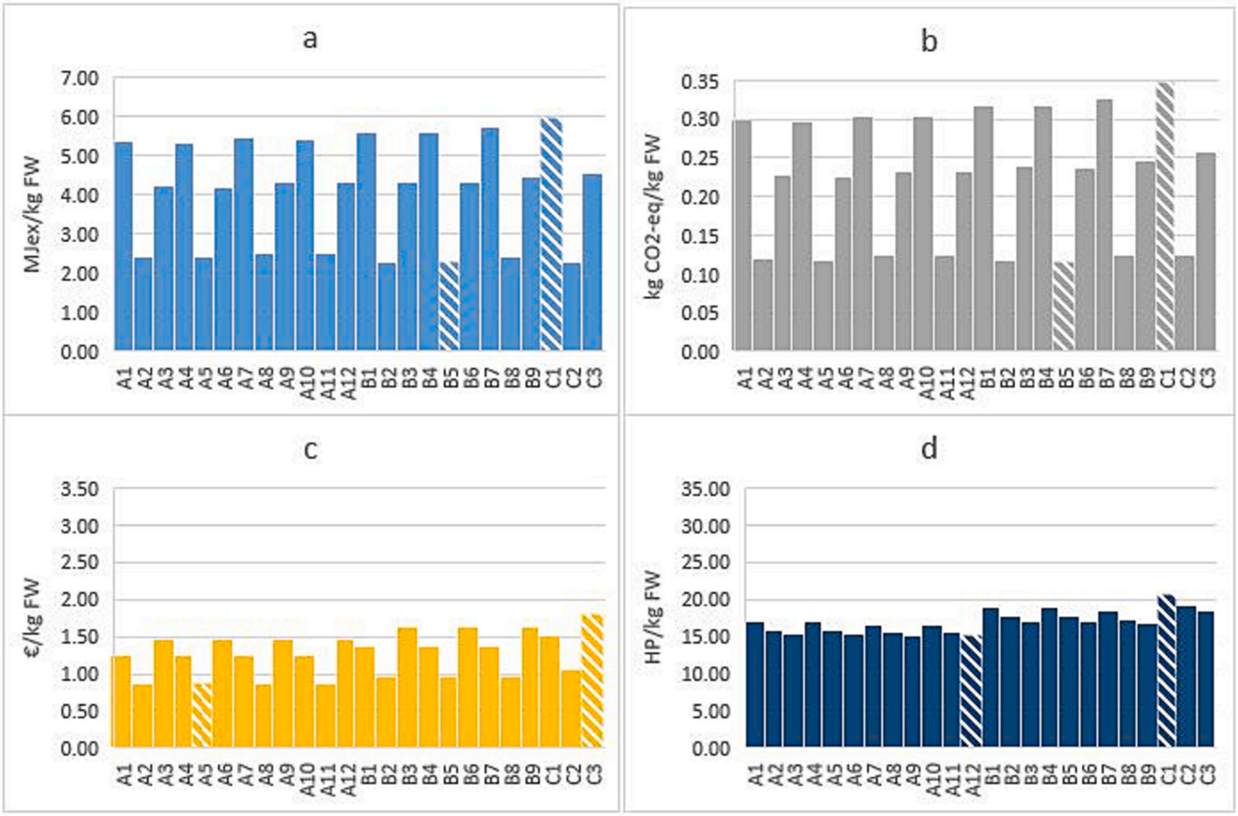


Fig. 7. Average MJex/kg FW (a), kg CO2-eq/kg FW (b), €/kg FW (c), and HP/kg FW (d) for each scale-up scenario. Best and worst performing scenario indicated by striped diagonal shading.

sites be optimally located and designed to optimize the equipment and reduce the transport needed per longline. Additional strategies not considered in this study which could improve the environmental and economic performance of cultivation pathways include yield-improving methods such as integrated multi-trophic aquaculture [2], in which seaweed farms use the nutrient effluent of nearby aquaculture production to boost yields, and multiple partial harvesting [26], in which longlines remain in the sea year-round and harvesting takes place multiple times per year. The impact of different types of deployment equipment on risk of damage and the impact of sustainable fuels on transport emissions and costs could also be investigated in future studies.

Although many uncertainties exist regarding the future of seaweed production systems, Ireland's estimated wild harvest exploitation limit of 240,618 t FW/year means that the upscaling of current wild harvesting methods alone will not be sufficient to reach future production targets. Furthermore, the Irish Government aims to increase the amount of Marine Protected Areas (MPAs) to 30 % of Ireland's marine area [70]. This would certainly limit the wild harvesting potential, as activist groups have called for a ban of all mechanical harvesting in these areas [71]. This prompts the question of whether the European seaweed production targets are warranted. To meet the European Union's ambitious 2030 targets, a significant proportion of future Irish seaweed production would need to come from cultivation. While spatially feasible, the huge upscaling of cultivation would take considerable resources, emit significant amounts of GHGs, and be very costly. More research on the influence of location and farm design should therefore be conducted before such significant upscaling. Additionally, consideration should be taken for the utility of the end product, both from an environmental perspective and based on economic and societal value. Finally, the upscaling situation becomes even more complex when considering preservation pathways. Seaweed harvesting is highly seasonal with large amounts of seaweed simultaneously produced at the same time once per year. As harvested seaweed needs to be preserved rapidly and as there exists a limited number of processing facilities in Ireland [22], preservation will pose a significant upscaling bottleneck. Furthermore, the currently established drying preservation method is energy intensive and thus has high environmental impacts and economic costs. Upscaling of seaweed production therefore requires not only consideration of alternative production pathways, but also of alternative preservation pathways and supply chains. Environmental and economic impacts of preservation methods have been assessed in previous studies [1,2,20,21,24], however, social impacts, the feasibility of scaling up, and the effectiveness of different methods in preserving product qualities, could be topics of future studies.

5. Conclusion

This study determines the environmental, economic, and social impacts of Irish seaweed production pathways which could be employed to meet future production targets. Wild harvesting is less costly than seaweed cultivation and is found to be economically viable for all pathways. Furthermore, despite the direct extraction of natural resources, manual wild harvesting pathways are found to have relatively low environmental impacts. Mechanization of wild harvesting decreases social benefits (less labour demand) while increasing environmental impacts and costs (more fuel demand) compared to manual wild harvesting methods; however, as it provides access to wild kelp resources, it may be needed to meet future production targets. Seaweed cultivation, on the other hand, has a better social performance compared to wild harvesting through the creation of more jobs. However, due to infrastructure and transport needs, seaweed cultivation has high environmental and economic costs. While seaweed cultivation is only found to be economically viable at higher selling prices, it is essential if a significant upscale in production is required. Thus, the choice of farm location, configuration, and size are essential to influencing the overall impacts of the sector. While trade-offs are inevitable and thus there is not objective answer as to which is the most sustainable option, the hope is that the results provided in this study can help stakeholders make informed decisions for the developing industry.

CRediT authorship contribution statement

Charlene Vance: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Priya Pollard:** Investigation, Writing – review & editing. **Julie Maguire:** Resources, Investigation, Writing – review & editing. **Joseph Sweeney:** Supervision, Writing – review & editing. **Fionnuala Murphy:** Resources, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The authors and project are affiliated with Bantry Marine Research Station, which is a commercial enterprise that owns and operates seaweed cultivation sites in Ireland. The role of Bantry Marine Research Station was limited to data provision and to the best of the authors' knowledge does not cause a conflict of interest.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.algal.2023.103294.

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