*Environmental and Climate Technologies*
2026, vol. 30, no. 1, pp. 155–173
https://doi.org/10.2478/rtuect-2026-0011
*https://content.sciendo.com*

RIGA TECHNICAL UNIVERSITY

# An Explorative Social Life Cycle Assessment for Wild Harvest and Cultivation of *F. lumbricalis* in the Baltic Sea Region

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Received 07.10.2025; accepted 01.02.2026

***Abstract* – This study applies a Social Life Cycle Assessment (S-LCA) to evaluate the social impacts of *Furcellaria lumbricalis* red macroalgae production through wild harvesting (WH) and offshore cultivation (OC) in the Baltic Sea Region. As macroalgae gain interest in food, feed, and biorefinery applications, understanding the social sustainability of different production systems becomes increasingly important. The assessment follows UNEP/SETAC (2020) guidelines and the ISO 14075:2024 framework, adopting a cradle-to-gate system boundary. The Social Hotspot Database (SHDB) was used to assess 30 social indicators under two scenarios: (1) WH, the predominant method in Estonia, and (2) a hypothetical OC system. The functional unit was defined as 1 USD generated over an 8-hour working day, and Monte Carlo simulations were conducted to address uncertainty. Results show that WH presents lower social risks (432.85 Pt) than OC (719.51 Pt). In WH, the main risks were linked to occupational hazards and potential forced labour during harvesting activities. In OC, boat maintenance contributed the highest share of impacts due to extended operational requirements. Key risks across both scenarios included injuries and fatalities, forced labour, and discrimination. The findings suggest that WH is the more socially sustainable option, supporting traditional employment and local communities. However, improvements in occupational health and safety remain necessary. OC, despite its potential scalability, poses higher social risks that call for strengthened labour standards and governance. Future research should incorporate site-specific data and stakeholder engagement to enhance the robustness and relevance of S-LCA in macroalgae value chains.**

***Keywords* – Blue bioeconomy; Life Cycle Thinking; macroalgae production; Social Hotspot; database; Social Life Cycle Assessment.**

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| **Nomenclature** | |
|---|---|
| EU | European Union |
| FU | Functional unit |
| LCA | Life Cycle Assessment |
| LCI | Life Cycle Inventory |
| mrheq | Medium risk-hour equivalents |
| OC | Offshore cultivation |
| Pt | Points (annual global per-capita normalized/weighted results in the applied SHDB method) |
| S-LCA | Social Life Cycle Assessment |
| SHDB | Social Hotspot Database |
| USD | United States dollar |
| WH | Wild harvesting |

## 1. INTRODUCTION

Macroalgae are a highly versatile resource, suitable for direct human consumption and for processing into various products such as food additives [1], animal feed [2], fertilizers [3], biofuels [4], cosmetics [5], and pharmaceuticals [6]. This versatility has driven a steady increase in macroalgae production, reaching 35 million tons in 2020 [7]. Asian countries dominate this sector, accounting for 98 % of total production [8]. Although Europe's share remains modest, it is expanding rapidly, with a growth rate of +90 % between 2010 and 2020 [7], driven by European Union initiatives.

One notable milestone is the EU Algae Initiative [9], adopted in 2022. It establishes a strategic framework with 23 actions aimed at promoting algae production, streamlining regulatory processes, and raising public awareness of its benefits. Additionally, the EU4Algae Platform [10] serves as an interactive hub to foster collaboration and knowledge exchange within the European algae industry. The KELP-EU Project [11], funded by the European Maritime and Fisheries Fund, emphasizes sustainable farming practices and scalable biorefinery processes, including a pilot plant for large-scale production. The Joint Research Centre has further contributed with guidelines for sustainable European seaweed aquaculture [12], aiming to meet growing global demand while ensuring environmental protection.

In contrast to global trends, European seaweed production primarily relies on wild harvesting rather than cultivation. In 2019, 99.5 % of European production (approximately 294 744 tons) originated from wild harvests, with only 0.5 % (1450 tons) sourced from cultivation [13]. Seaweed harvesting holds significant social value for European coastal communities [14], creating employment and supporting local economies across various industries [15]. Traditional manual seaweed collection fosters community engagement and preserves cultural heritage [16]. However, sustainable management practices and effective regulatory frameworks are essential to ensure long-term socio-economic benefits.

Despite its sustainable potential to produce food, feed, and biomaterials, the European seaweed industry faces challenges. The current focus on large-scale, techno-innovative, centralized processes limits its capacity for broader social transformation [17]. Few studies consider these social aspects; for instance, Albrecht (2023) [18] discusses Norway's pioneering role in the "*seaweed revolution*." While policy narratives emphasize economic opportunities and coastal revitalization, the socio-economic impact on Norwegian coastal communities remains limited. Reliance on centralized processing infrastructure and seasonal operations constrain job creation and restrict community engagement. Furthermore, dominant narratives about green growth often overlook challenges like scalability, environmental risks, and the exclusion of localized farming models that could deliver more equitable socio-economic benefits.

To assess the social benefits of such systems, Social Life Cycle Assessment (S-LCA) has emerged as a robust methodology [19]. S-LCA evaluates the social impacts of production systems, emphasizing stakeholder well-being [20], ethical considerations, and social equity [21]. Unlike environmental LCA, which focuses on environmental impacts, S-LCA provides insights into human and societal implications. Although theoretical discussions on S-LCA are abundant, practical applications remain limited [22], especially in macroalgae-related practices. In the Baltic Sea Region, the application of S-LCA is virtually nonexistent, with the current literature primarily addressing environmental and economic aspects. To our knowledge, aside from this study, only one other research effort [16] has applied S-LCA to a macroalgae supply chain in Europe. However, that study focused solely on "*individual well-being*" as a social indicator, neglecting the comprehensive spectrum of social indicators and stakeholders, such as workers, local communities, and value chain actors.

The objective of this study is to address this gap by applying S-LCA to evaluate the social implications of the macroalgae production value chain. Using the Social Hotspot Database, this research identifies opportunities and risks within the system, starting with wild harvesting (the predominant technique in Europe) of *Furcellaria lumbricalis* (an abundant macroalgae specimen endemic to the Baltic Sea Region) as the baseline scenario. Additionally, a second scenario involving macroalgae cultivation is analysed to incorporate an alternative system. The study follows the UNEP/SETAC 2020 guidelines [23] and newly developed ISO 14075:2024 [24] to ensure adherence to recognized and reproducible frameworks. By identifying social hotspots within each system, this research aims to raise awareness of the social implications of seaweed production and contribute to the development of more sustainable and inclusive practices.

## 2. Methods

### *2.1. Social Life Cycle Assessment Definition*

The S-LCA in this study follows the ISO 14075:2024 framework [24], which structures the assessment based on life cycle thinking principles. This framework encompasses key stages, including goal and scope definition, functional unit selection, system boundary determination, and inventory development, ensuring a systematic and standardized approach to the analysis.

#### *2.1.1. Goal and scope definition*

The primary goal of this study is to explore the social dimensions associated with a seaweed value chain, starting from the biomass collection methods and conducting an S-LCA of different seaweed harvesting and cultivation techniques.

In this way, the specific objective of the research is to identify key social issues linked to the wild harvesting (i.e., reference scenario) of the red seaweed *F. lumbricalis* at a national scale through a social hotspot analysis. *F. lumbricalis* was selected due to its abundant availability in the Baltic Sea within the Estonian territory [25], where the harvesting activities occur, coupled with an interest in identifying sustainable utilization pathways for this resource [26]. Wild harvesting was chosen for reference analysis as it is the predominant method for collecting this species [27] and is underrepresented in existing literature [28].

Additionally, the S-LCA includes an exploratory scenario involving a hypothetical offshore cultivation system for *F. lumbricalis*. This scenario was developed to assess the potential social impacts of such a system, as no documented examples of industrial or literature-based offshore cultivation for *F. lumbricalis* currently exist. By incorporating this hypothetical scenario, the study broadens its scope, facilitating a more comprehensive social hotspot analysis. This approach enables the identification of both positive and negative social aspects of each system, providing insights beyond what a single-scenario analysis could achieve.

To ensure comparability across scenarios, the functional unit (FU) is defined as 1 USD generated during an 8-hour standard working day for each system. This FU reflects the unique characteristics of the systems under study and establishes a consistent basis for assessment.

### *2.1.2. System description*

The general system boundaries description can be defined as cradle-to-gate, and the geographical boundaries are set as Estonia. The system modelled for the first scenario, wild harvesting (WH), was adapted from a previous study [27]. Fig. 1 illustrates the system's process scheme for the WH scenario, which is comprised of four main stages. The core stage is the wild harvesting of *F. lumbricalis* in Kassari Bay, located between the Estonian islands of Hiiumaa and Saaremaa, approximately 40 minutes by a diesel engine boat from the shore. The remaining stages include the boat transport to and from the harvesting site, unloading the boat, and a boat maintenance period, which requires one month of service annually.

For the WH scenario, considering the time frame of FU (i.e., 1 day of 8 working hours), the amount of fresh *F. lumbricalis* harvested is equal to 10 tons.


Fig. 1. System diagram for the WH scenario.

Fig. 2 presents the scheme for the offshore cultivation (OC) setup. The modelling of the life cycle inventory is based on the literature [29], e.g., an artificial substrate cultivation system for *F. lumbricalis* seaweed.  All data have been normalized to achieve the same biomass yield (i.e., 10 tons) as in the WH scenario.

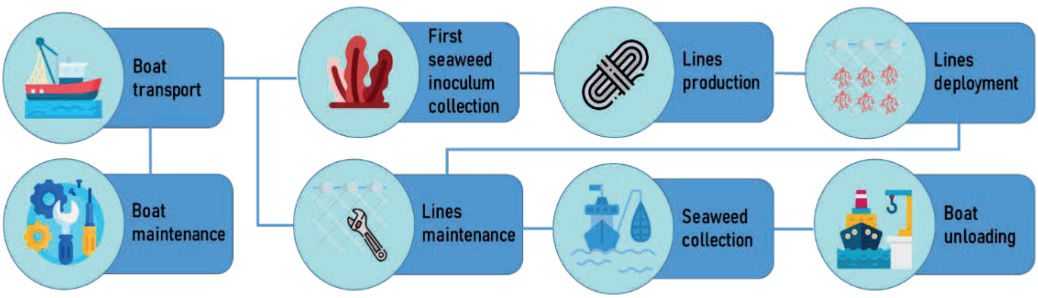


Fig. 2. System diagram for the OC scenario.

The process begins with the collection of the initial inoculum of *F. lumbricalis* from Kassari Bay, the same area used in the WH scenario. The biomass is then implanted into specialized nylon mesh bags (with a plastic frame inside; Ø 5.5 cm, height 20 cm) with a mesh size of 1 mm. The material is carefully selected to minimize light reduction inside the bags. After deployment, the lines are submerged at a depth of 4 meters and left to grow for 3 months. The location is assumed to be always Kassari Bay to maintain the best natural environmental conditions. During this period, the growth rate is reported to increase by 155 %. Routine maintenance of the lines is assumed to occur once per month over the 3-month period.

At the end of the 3 months, the cultivated *F. lumbricalis* reached 10 tons of amount, it was harvested, and the boat was unloaded at the harbour, following the same procedure as in the WH scenario. As with WH, the OC scenario also includes a 1-month annual maintenance period for the boat.

### *2.2. Social Hotspot Database Definition and Implementation*

The Social Hotspot Database (SHDB) was employed to identify and analyse potential social risks within the product supply chains, focusing on areas where significant social issues may arise in the WH and OC systems. The SHDB serves as a comprehensive resource, integrating data from global organizations such as the International Labour Organization and the World Bank to map risks related to various social issues [30]. A total of 30 were assessed, including child labour, forced labour, inadequate working conditions, wages, and health and safety.

Commonly applied in S-LCA, the SHDB uses a risk-based approach to assess social impacts, helping users identify regions of higher risk within their supply chains. In the discussion of results (Section 3.6), an example will be provided to illustrate how social impacts extend throughout the entire value chain. The SHDB covers a wide range of social issues across more than 150 sectors and nearly 200 countries [30]. The database is transparent and relies on recognized data sources to provide reliable insights. Its application has been widely adopted in various sectors. For example, Backers and Traverso (2022) [22] used it to map potential social risks across carbon-reinforced concrete supply chains in different countries, while Zamani *et al*. (2016) [31] employed it to identify social hotspots within the Swedish clothing industry.

In this study, the SHDB processes selected are specific to Estonia, as stated in the definition of system boundaries. The SHDB was then used to identify the sector that best represents the operations performed. This selection was based on the descriptions provided in the SHDB. It should be noted that some operations had to be simplified, as there is no direct one-to-one match for certain processes. In these cases, the SHDB operation most closely aligned with the actual activity was selected, the so-called *proxy*.

Table 1 presents the SHDB processes selected for the WH scenario. In this case, *proxy* processes were utilized for certain activities.

TABLE 1. SHDB PROCESSES DESCRIPTION FOR THE WH SCENARIO

| Process stage | SHDB process | Description from SHDB |
|---|---|---|
| Seaweed harvesting | Fishing (fsh)/EST U | Fishing in Estonia |
| Transport to harbour | Water transport (wtp)/EST U | Water transport in Estonia |
| Boat unloading | Manufactures nec (omf)/EST U | Other manufacturing Estonia |
| Boat maintenance | Trade (trd)/EST U | Retail, wholesale, and repair services in Estonia |

For instance, boat unloading is represented by the "manufactures nec (omf)/EST U" process, a generic manufacturing *proxy* not explicitly tailored to boat unloading. Similarly, boat maintenance is modelled using the "trade (trd)/EST U" process, which encompasses repair services but does not explicitly specify boat maintenance. However, the remaining processes, such as seaweed harvesting and transport to the harbour, are more specific and adequately represented by the SHDB, reflecting their characteristics accurately.

Table 2 outlines the SHDB processes selected for the OC scenario. Notably, the system stages "first seaweed inoculum collection" and "seaweed collection" have been combined, as both involve the collection of *F. lumbricalis*. The *proxy* processes used are similar to those in the WH scenario, with boat unloading and boat maintenance represented by "manufactures nec (omf)/EST U" and "trade (trd)/EST U," respectively. Additionally, line deployment and line maintenance are modelled using the "Fishing (fsh)/EST U" *proxy*, as these operations are analogous and comparable to fishing activities. Conversely, boat transport, first seaweed inoculum collection, and line production are well-represented within the SHDB, eliminating the need for *proxy* processes in these cases.

TABLE 2. SHDB PROCESSES DESCRIPTION FOR THE OC SCENARIO

| Process stage | SHDB process | Description from SHDB |
|---|---|---|
| Boat transport | Water transport (wtp)/EST U | Water transport in Estonia |
| First seaweed inoculum collection<br>Seaweed collection | Fishing (fsh)/EST U | Fishing in Estonia |
| Lines production | Chemical, rubber, plastic products (crp)/EST U | Chemical, rubber, and plastic products in Estonia |
| Lines deployments | Fishing (fsh)/EST U | Fishing in Estonia |
| Lines maintenance | Fishing (fsh)/EST U | Fishing in Estonia |
| Boat unloading | Manufactures nec (omf)/EST U | Other manufacturing Estonia |
| Boat maintenance | Trade (trd)/EST U | Retail, wholesale, and repair services in Estonia |

As a final remark, it is important to emphasize that in the SHDB, process inputs are required to be assigned a monetary value (i.e., USD 2011). In this study, due to the absence of precise data on the total monetary value of the systems, a reverse approach was implemented. Specifically, the model uses 1 USD produced during an 8-hour workday as the input, corresponding to the time frame of the FU for the WH and OC systems. The allocation factors reported in Tables 4 and 5 were then applied accordingly.

### *2.2.1. Calculation method definition for the SHDB*

This study used the "Social Hotspot 2022 Category Method w Norm," accessible via the SHDB on *SimaPro software version 9.5*. Figure 3 illustrates a schematic representation of this approach.

The Social Hotspot 2022 Subcategory Method w Norm / global per capita annual encompasses 30 social risk sub-categories and a smaller set of 5 broad social damage risk categories [32]. In each case, the characterization of sub-categories involves multiplying the LCI inventory results by a factor that reflects the relative probability of occurrence of adverse working or community conditions for a given indicator. The unit of measurement is medium risk-hour equivalents ($mrh_{eq}$).

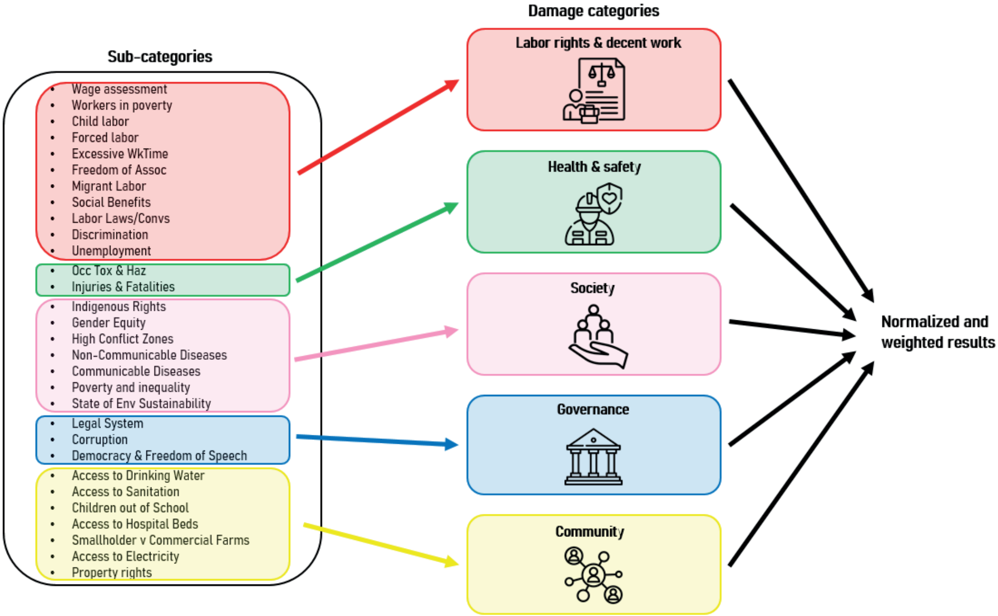


Fig. 3. provides a schematic visualization of the Social Hotspot 2022 Subcategory Method with normalization (Norm.).

These probability levels are expressed relative to the likelihood of the adverse condition occurring at a medium risk level. A low risk indicates about one-tenth of the likelihood of occurrence compared to medium risk, so the characterization factor for low risk is 1 medium risk-hour equivalent. Very high risk corresponds to a roughly 10-fold increase in likelihood compared to medium risk, with a characterization factor of 10 medium risk-hour equivalents per very high risk-hour. High risk indicates about half the likelihood of very high risk, or five times that of medium risk, resulting in a characterization factor of 5 medium risk-hour equivalents per high risk-hour [32].

The sub-category characterization results are then aggregated using a “damage assessment” approach at the category level. This method, referred to as the “Category method,” generates weighted sums of sub-category results for each category. The weights are designed so that category-level results are not biased by the number of sub-categories within each category. As a result, categories with fewer sub-categories will have scores comparable to those with many sub-categories, provided the risk levels are the same. One version of the Category method includes normalization data at the category level and allows for optional user-defined weighting of category results.

Finally, a weighting procedure is applied, with results expressed in annual global per capita units (Pt), representing total per capita annual medium risk-hour equivalents for each sub-category based on the total global economic output in one year.

### *2.3. Sensitivity and Uncertainty Analysis*

The study compared two scenarios, WH and OC, but key uncertainties exist within these systems. The modelled systems represent hypothetical applications, as this is the first example of an S-LCA applied to activities related to macroalgae harvesting and production. Consequently, the parameters defined are subject to high levels of uncertainty. This is particularly evident in the allocation factors, which determine the time required for the various activities described in Fig. 1 and Fig. 2.

To address these uncertainties, a Monte Carlo simulation was performed directly using SimaPro software. The simulation employed a normal distribution to vary the initial input allocations within a defined range of values for a total of 5000 simulations. The range of variation was determined based on the degree of uncertainty and the weight of each parameter in the allocation process. Further details on the allocation factors and their uncertainties are provided in Table 3.

TABLE 3. DEFINITIONS OF PARAMETER VARIATIONS FOR THE MONTE CARLO SIMULATION

| Process stage | Range of values |
|---|---|
| **WH scenario** | |
| Seaweed harvesting | ±30 % |
| Transport to harbour | ±10 % |
| Boat unloading | ±20 % |
| Boat maintenance | ±20 % |
| **OC scenario** | |
| Boat transport | ±10 % |
| First seaweed inoculum collection & seaweed collection | ±30 % |
| Lines production | ±10 % |
| Lines deployments | ±30 % |
| Lines maintenance | ±30 % |
| Boat unloading | ±20 % |
| Boat maintenance | ±20 % |

The range of values for the Monte Carlo simulation was determined by assessing the processes with the highest uncertainties in the time required to perform specific operations. For the WH scenario, seaweed harvesting, and for the OC scenario, stages such as first seaweed inoculum collection, seaweed collection, line deployment, and line maintenance were identified as the most uncertain. These operations, conducted in open sea conditions, are heavily influenced by weather, which can significantly impact the time needed to complete them. Consequently, a larger uncertainty range (±30 %) was assigned to these stages. An intermediate uncertainty range (±20 %) was applied to boat maintenance and unloading. These operations, while primarily associated with general boat activities, can vary depending on the frequency and type of boat usage. Assigning an intermediate value is considered a conservative yet reasonable approach to account for this variability. For more stable activities such as transport to the harbour and line production, a lower uncertainty range (±10 %) was assumed, as these processes are generally fixed and less susceptible to external factors.

The Monte Carlo simulation results play a crucial role in refining the analysis by establishing a broader range within which the outcomes may fall. This approach enhances the reliability of the findings by accounting for potential variations, thereby reducing overall uncertainty. It also provides a clearer understanding of the system's performance under varying conditions, aiming to mitigate the uncertainties associated with the initial system data modelling.

# 3. Results

## 3.1. Life Cycle Inventory

In this chapter, the life cycle inventories (LCI) of the two scenarios are reported, and how the allocation is performed. Table 4 shows the LCI for the WH scenario.

TABLE 4. LCI FOR SOCIAL LIFE CYCLE IMPACT ASSESSMENT SCENARIOS FOR THE WH SCENARIO

| Stage | Description | Assumption/calculation | Daily time to perform the operation | Allocation to FU |
|---|---|---|---|---|
| Seaweed harvesting | Harvesting by throwling. Boat capacity up to 12 tons | Assumed to be the remaining time of the 8 hours, subtracting the time required by the other operations | 4.50 hours | 56 % |
| Transport to harbour | 40 minutes of sailing distance | Considered 2 times, for going and coming back | 1.33 hours | 17 % |
| Boat unloading | Electric unloader | – | 1.50 hours | 19 % |
| Boat maintenance | 1 time per year (1 month) | Normalization of the 1-month period to the 8 hours of FU | 0.67 hours | 8 % |

Table 5 provides the information for the OC scenario. The data were initially plotted over the 3-month period required to reach 10 tons of *F. lumbricalis* cultivated, and then these values were subsequently normalized to the functional unit.

TABLE 5. LCI FOR THE OFFSHORE CULTIVATION SCENARIO

| Stage | Description | Assumption/calculation | Time to perform the operation (3 months) | Normalization on the FU | Allocation to FU |
|---|---|---|---|---|---|
| Boat transport | 40 minutes of sailing distance | It includes boat transport for the first seaweed inoculum collection, for the lines' deployment, lines maintenance, and for the final seaweed collection. Considered 2 times, for going and coming back. | 1.33 hours (for 1 single trip, go and back) 6.00 hours (for all the trips) | 0.24 hours | 2.96 % |
| First seaweed inoculum collection | 603 kg are needed to obtain 10 000 kg of fresh *F. lumbricalis* | It has been calculated, knowing the rate and the time of growth, and the final target amount | 0.50 hours | 0.020 hours | 0.25 % |
| Lines production | Nylon mesh bags | The amount of nylon required was calculated by normalizing data from the literature [33], resulting in a total of 33 kg for this case study. The production rate of nylon has been assumed to be 250 kg per 8-hour workday [34], and this value was normalized to match the 33 kg required for the system | 1.06 hours | 0.042 hours | 0.52 % |

| | | | | | |
|---|---|---|---|---|---|
| Lines deployments | – | Assumed half of the time needed for the seaweed collection | 2.25 hours | 0.089 hours | 1.11 % |
| Lines maintenance | 1 time per month | 3 times in total. Assumed is the same time needed for the line deployment | 6.75 hours | 0.27 hours | 3.33 % |
| Seaweed collection | – | Since the amount is the same, it is assumed to be the same as the wild harvesting | 4.50 hours | 0.18 hours | 2.22 % |
| Boat unloading | Electric unloader | Since the amount is the same, it is assumed to be the same as the wild harvesting | 1.50 hours | 0.059 hours | 0.74 % |
| Boat maintenance | 1 time per year (1 month) | Normalization of the 1-month period to the 3 months needed for the seaweed growth | 180 hours | 7.11 hours | 88.86 % |

In both scenarios, the LCI is simplified by calculating it based on the total work hours performed. This method facilitates a direct comparison between the two systems by focusing on the potential social risks associated with an individual worker in each system.

### *3.2. Wild Harvesting Results*

Table 6 shows the results of the sub-categories for the WH scenario. The results are reported with a colour scale from red (highest potential social risk) to green (lowest potential social risk).

TABLE 6. SUB-CATEGORIES RESULT FOR THE WH SCENARIO

| **Impact category** | **Seaweed harvesting** | **Maintenance of boat** | **Transport to the harbor** | **Boat unloading** | **Total** | **Unit** |
|---|---|---|---|---|---|---|
| Wage assessment | 0.01508 | 0.00454 | 0.00486 | 0.00695 | 0.0314 | mrheq |
| Workers in poverty | 0.01135 | 0.00301 | 0.00216 | 0.00433 | 0.0208 | mrheq |
| Child Labour | 0.01274 | 0.00355 | 0.00197 | 0.00519 | 0.0234 | mrheq |
| Forced Labour | 0.02167 | 0.00576 | 0.00506 | 0.00946 | 0.0419 | mrheq |
| Excessive WkTime | 0.01588 | 0.00431 | 0.00378 | 0.00704 | 0.0310 | mrheq |
| Freedom of Assoc | 0.01269 | 0.00310 | 0.00248 | 0.00641 | 0.0247 | mrheq |
| Migrant Labour | 0.00982 | 0.00241 | 0.00201 | 0.00421 | 0.0185 | mrheq |
| Social Benefits | 0.00711 | 0.00190 | 0.00116 | 0.00352 | 0.0137 | mrheq |
| Labour Laws/Convs | 0.00387 | 0.00119 | 0.00125 | 0.00152 | 0.0078 | mrheq |
| Discrimination | 0.01868 | 0.00529 | 0.00403 | 0.00811 | 0.0361 | mrheq |
| Unemployment | 0.00666 | 0.00165 | 0.00170 | 0.00274 | 0.0127 | mrheq |
| Occ Tox & Haz | 0.01799 | 0.00476 | 0.00298 | 0.00860 | 0.0343 | mrheq |
| Injuries & Fatalities | 0.02456 | 0.00658 | 0.00692 | 0.01012 | 0.0482 | mrheq |
| Indigenous Rights | 0.00537 | 0.00143 | 0.00073 | 0.00230 | 0.0098 | mrheq |
| Gender Equity | 0.00759 | 0.00214 | 0.00114 | 0.00311 | 0.0140 | mrheq |
| High Conflict Zones | 0.00958 | 0.00235 | 0.00222 | 0.00472 | 0.0189 | mrheq |
| Non-Communicable Diseases | 0.00256 | 0.00058 | 0.00045 | 0.00114 | 0.0047 | mrheq |
| Communicable Diseases | 0.00747 | 0.00210 | 0.00103 | 0.00296 | 0.0136 | mrheq |

| | | | | | | |
|---|---|---|---|---|---|---|
| Poverty and inequality | 0.01278 | 0.00342 | 0.00240 | 0.00583 | 0.0244 | mrheq |
| State of Env Sustainability | 0.01572 | 0.00438 | 0.00237 | 0.00691 | 0.0294 | mrheq |
| Legal System | 0.01243 | 0.00312 | 0.00397 | 0.00569 | 0.0252 | mrheq |
| Corruption | 0.00680 | 0.00159 | 0.00190 | 0.00274 | 0.0130 | mrheq |
| Democracy &Freedom of Speech | 0.01739 | 0.00457 | 0.00633 | 0.00873 | 0.0370 | mrheq |
| Access to Drinking Water | 0.00799 | 0.00212 | 0.00118 | 0.00315 | 0.0144 | mrheq |
| Access to Sanitation | 0.01306 | 0.00378 | 0.00194 | 0.00522 | 0.0240 | mrheq |
| Children out of School | 0.00922 | 0.00238 | 0.00192 | 0.00463 | 0.0182 | mrheq |
| Access to Hospital Beds | 0.01176 | 0.00321 | 0.00235 | 0.00449 | 0.0218 | mrheq |
| Smallholder v Commercial Farms | 0.00255 | 0.00062 | 0.00028 | 0.00231 | 0.0058 | mrheq |
| Access to Electricity | 0.00547 | 0.00159 | 0.00048 | 0.00218 | 0.0097 | mrheq |
| Property rights | 0.01390 | 0.00393 | 0.00220 | 0.00546 | 0.0255 | mrheq |

It is clear that the harvesting operation is the stage with the highest potential social risk, followed by the boat unloading procedures. Among the indicators, *Injuries & Fatalities* is the one with the potentially higher risk (0.0482 mrheq). Also notable are the *Forced Labour* (0.0419 mrheq) and *Discrimination* (0.0361 mrheq).

For a better understanding of the results, Fig. 4 shows the normalized and weighted results divided into the damage categories.

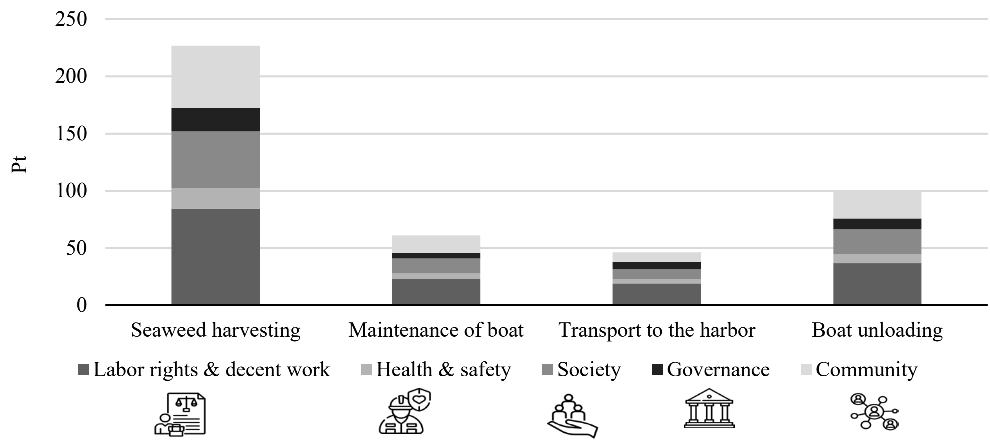


Fig. 4. Normalized and weighted results for the WH scenario.

Seaweed harvesting is the stage with the highest potential social risk (226.85 Pt). Among the single indicators, the most predominant are *Access to electricity* (22.36 Pt), *Labour Law/Convs* (20.51 Pt), and the *Occ Tox & Haz* (18.50 Pt). The damage categories with the most relevant input are *Labour rights & decent work* (163.45 Pt), *Community* (100.82 Pt), and *Society* (92.05 Pt). Fig. 5 provides a better picture of the indicators that contribute mostly to these 3 categories.

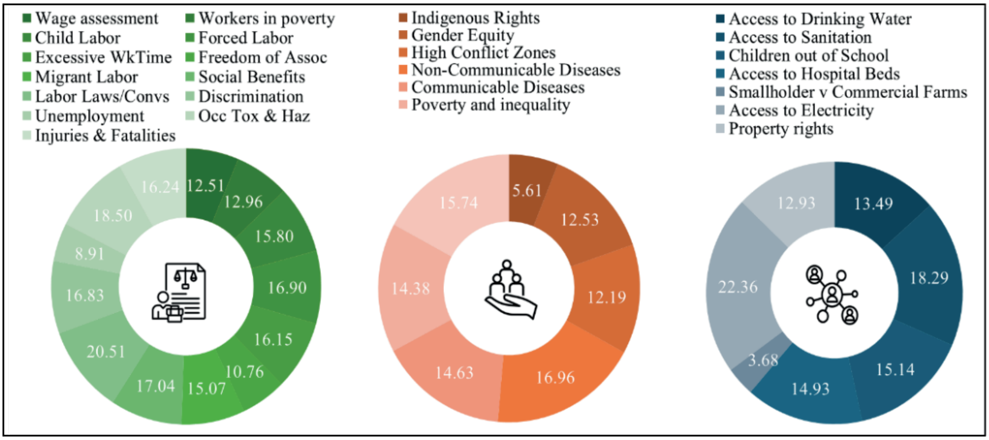


Fig. 5. Single sub-categories normalized and weighted impacts for *Labour rights & decent work*, *Society*, and *Community* categories in the WH scenario.

### 3.3. *Cultivation Results*

The results for the sub-categories in the OC scenario are reported in the Annex.

In offshore cultivation, boat maintenance is the process that carries the highest potential social impact. This is due to the longer time allocated to maintenance, as the 3-month seaweed growth period increases the relevance of maintenance activities. Similar to wild harvesting, the social indicators with the greatest impact are *Injuries & Fatalities* (0.0779 mrheq), *Forced Labour* (0.0681 mrheq), and *Discrimination* (0.0622 mrheq).

Fig. 6 reports the results normalized, weighted, and divided per system stage.

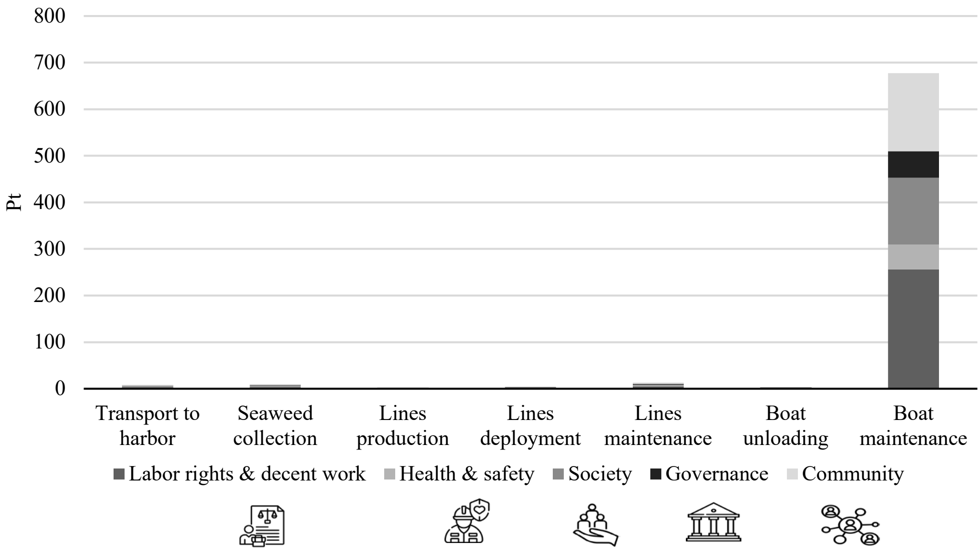


Fig. 6. Normalized and weighted results for the OC scenario.

The single indicators with the highest impact are *Access to electricity* (40.59 Pt), *Labour Law/Convs* (34.66 Pt), and *Access to Sanitation* (32.01 Pt). For boat maintenance, the damage categories of greatest concern are *Labour rights & decent work* (271.99 Pt), *Community* (177.06 Pt), and *Society* (152.58 Pt). These categories are further broken down in Fig. 7, providing more detailed insights into the specific social impacts within each category.

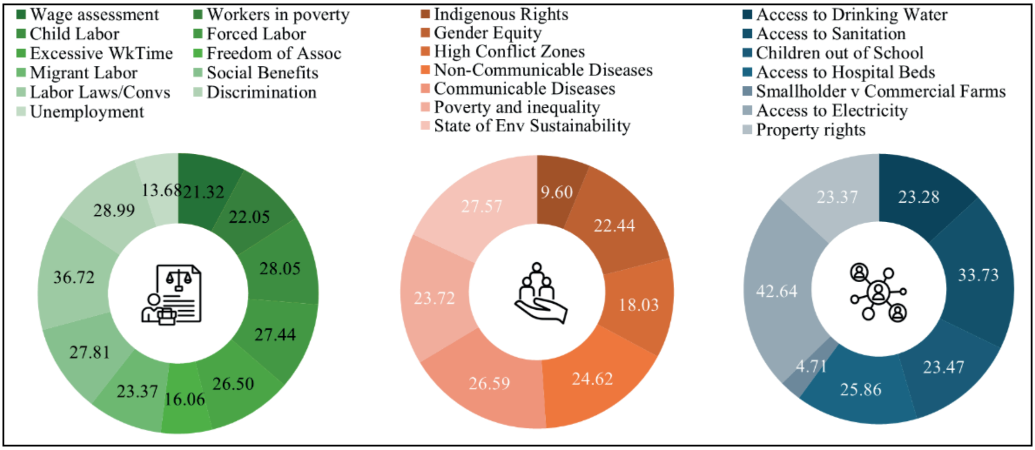


Fig. 7. Single sub-categories normalized and weighted impacts for *Labour rights & decent work*, *Health & safety*, and *Community* categories in the OC scenario.

### 3.4. Comparison Results

Fig. 8 provides a final comparison of the two scenarios.

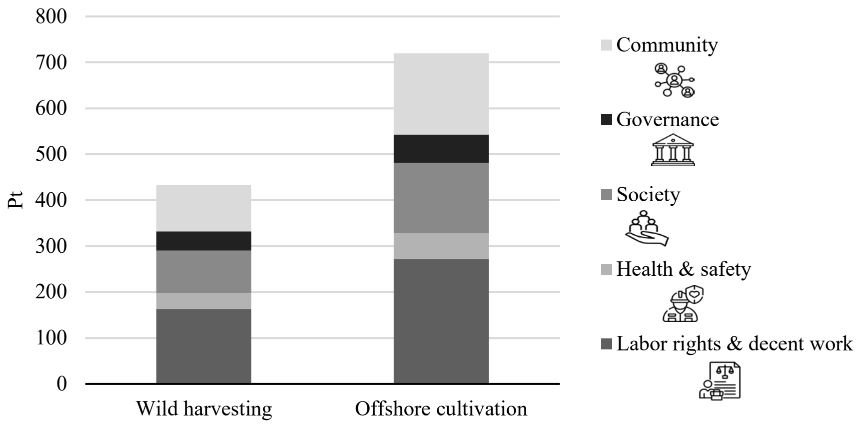


Fig. 8. Comparison results for the WH and OC scenarios.

The comparative results demonstrate that OC carries a substantially higher potential social impact than wild WH, with a total impact score of 719.51 Pt compared to 432.85 Pt, respectively. This indicates that OC poses greater social risks across the assessed categories, which include labour rights, community well-being, governance, and health and safety. The findings underscore the need for careful consideration of the socio-economic trade-offs associated with adopting offshore cultivation practices in the macroalgae sector.

To further validate these results and assess their robustness, a Monte Carlo simulation was conducted, providing a probabilistic analysis of potential outcomes in Fig. 9.

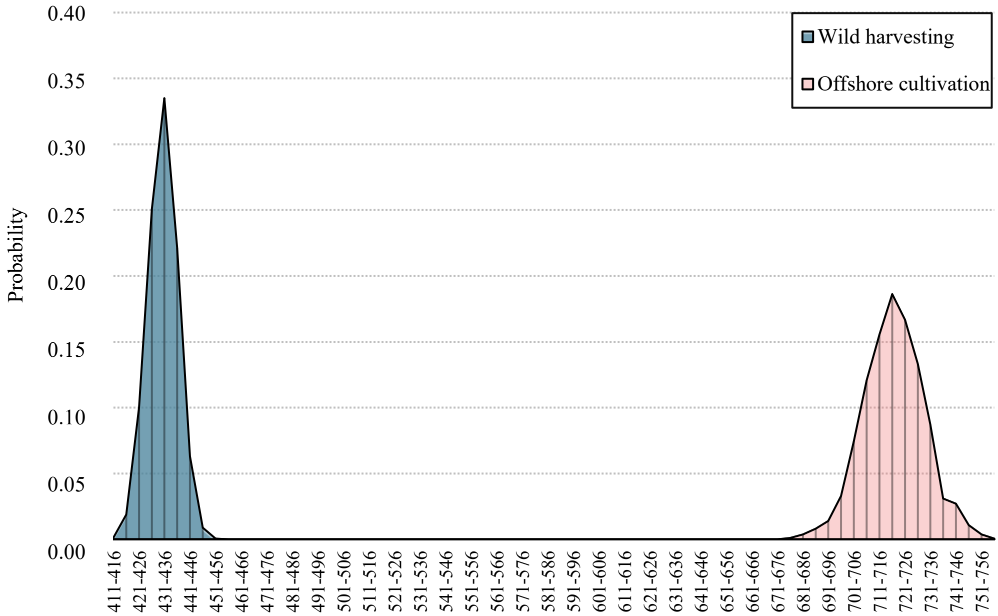


Fig. 9. Monte Carlo simulation results for the WH and OC scenarios.

Within the range of results from 5000 iterations of the simulation. For WH, the social impact values ranged between 411.5 Pt in the most favourable scenario and 454.5 Pt in the most unfavourable scenario. Conversely, OC exhibited a higher range, spanning from 678.1 Pt to 753.3 Pt

The absence of overlap between the ranges of the two scenarios highlights a clear and consistent preference for wild harvesting over offshore cultivation in terms of lower social impacts. This distinction reinforces the conclusion that, under current assumptions and data, there is no scenario in which offshore cultivation outperforms wild harvesting in terms of social sustainability. These findings provide strong evidence to support the prioritization of wild harvesting practices, at least until further advancements in offshore cultivation can mitigate their associated social risks.

### *3.5. Limitations and Uncertainties*

This study faces several limitations, primarily stemming from the inherent challenges in applying the S-LCA framework. The absence of standardized guidelines for the macroalgae sector and the limited availability of case studies in this domain pose significant obstacles to establishing a clear methodological pathway. Developing the approach required addressing multiple challenges, particularly in the allocation of impacts. This study employs a working-hour-based allocation to the FU, a methodology supported by Martinez-Blanco *et al*. (2014) [35] and Zamani *et al*. (2018) [31]. While this approach was deemed the most suitable given the data available, alternative methods, such as monetary-based allocations [36], could lead to differing results, underscoring the sensitivity of the outcomes to methodological choices.

Another limitation lies in the use of the SHDB, which relies on national-level data to estimate social risks. This broad scale makes it challenging to capture localized social impacts, such as those specific to small communities engaged in seaweed harvesting or cultivation. Although the results provide valuable initial insights through a hotspot analysis, they lack the granularity required to reflect the nuanced socio-economic realities of individual communities. Future studies could complement SHDB-based hotspot analyses with site-specific stakeholder data, such as worker surveys, interviews with local communities, or engagement with industry operators. Integrating bottom-up stakeholder information with SHDB results would allow a more nuanced representation of localized social conditions and improve the contextual accuracy of S-LCA outcomes.

Moreover, the modelled systems introduce varying degrees of uncertainty. While the WH system is based on real-world data, the OC system represents a hypothetical scenario. This introduces higher uncertainty in estimating social impacts for the OC scenario, as certain processes and their implications remain speculative. As new data becomes available, these hypothetical models can serve as a foundation for more accurate and comprehensive analyses.

The assumptions and data inputs used in this study also contribute to uncertainties. For instance, the time allocation for specific operations (e.g., harvesting, maintenance) and the weighting of processes are influenced by external factors such as weather conditions and operational variability. Sensitivity analyses, including Monte Carlo simulations, were conducted to address these uncertainties by exploring a range of possible outcomes. However, the results remain conditional on the assumptions made, particularly regarding the normalization of data input to the functional unit.

Lastly, the S-LCA methodology itself is more suited to evaluating existing, well-established systems [22]. Its application to emerging activities, such as large-scale seaweed cultivation, highlights the methodological challenges in assessing nascent industries with limited empirical data. Despite these limitations, this study offers a valuable starting point for understanding the social dimensions of macroalgae production in the Baltic Sea Region and provides a framework for future research in this area. Expanding the database, refining allocation methods, and integrating localized data will be essential to advancing S-LCA applications in this context.

### *3.6. Discussion*

This study evaluates the potential social impacts of WH and OC of *F. lumbricalis* in the Baltic Sea Region, providing insights into the social sustainability of two contrasting macroalgae production systems. The results indicate that WH exhibits lower social risks across all assessed impact categories, making it the more socially sustainable option under the assumptions of this study. In contrast, OC, while representing an innovative and potentially scalable approach, shows substantially higher social risks, largely driven by extended maintenance requirements during the three-month cultivation period.

In the WH scenario, the harvesting stage emerged as the most socially impactful process. The total normalized social impact score reached 432.85 Pt, with *Injuries & Fatalities*, *Forced Labour*, and *Discrimination* identified as the most critical sub-categories. At the damage-category level, *Labour Rights & Decent Work* and *Community* accounted for the largest contributions. Although WH supports traditional employment, local livelihoods, and cultural heritage in coastal communities, these results clearly indicate that occupational health and safety and labour conditions remain key areas requiring improvement.

An important insight emerging from the SHDB-based analysis is the spatial decoupling between production activities and social impacts. As illustrated in Fig. 10, the normalized indicator with the highest contribution, *Access to electricity*, is not primarily associated with Estonia, where harvesting operations occur, but rather with upstream supply chain countries such as the Ivory Coast and Ghana. Similarly, indicators such as *Occupational Toxicity and Hazards* show high contributions from countries like China. This finding highlights the globally distributed nature of social risks and underscores the importance of considering upstream supply chains when interpreting S-LCA results.

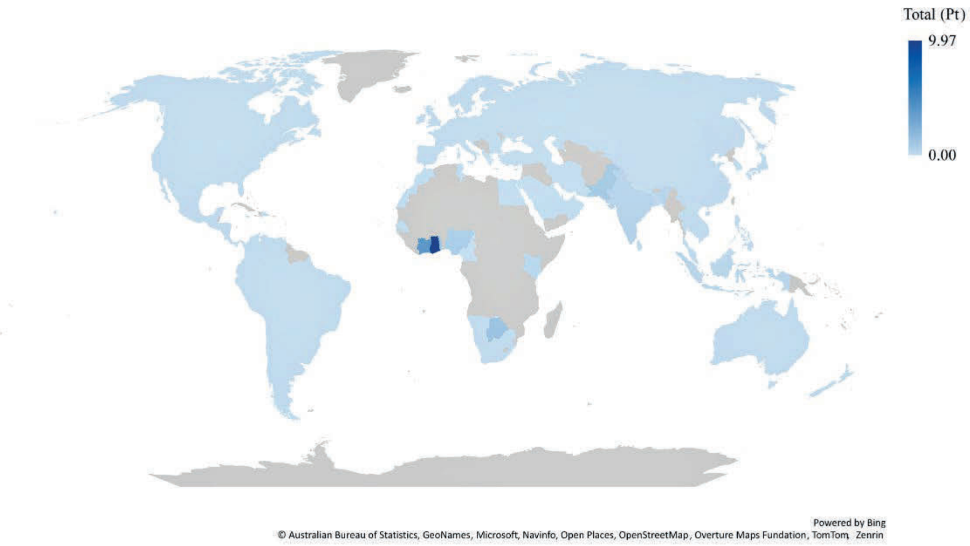


Fig. 10. Countries' hotspot analysis results for the normalized *access to electricity* indicator.

The OC scenario exhibited a markedly higher total social impact score of 719.51 Pt, driven primarily by the labour-intensive nature of line deployment and, in particular, prolonged boat maintenance activities. As in the WH scenario, *Injuries & Fatalities* and *Forced Labour* remained dominant contributors; however, their impacts were amplified by the longer operational timeframe and higher labour demands. These results reflect the broader challenges associated with industrialized and emerging production systems, including the need for robust labour governance, effective safety management, and institutional oversight.

It should be emphasized that the OC scenario represents a hypothetical system, as no industrial-scale offshore cultivation of *F. lumbricalis* currently exists in the Baltic Sea Region. Future empirical data derived from pilot or demonstration-scale offshore cultivation projects could play a critical role in validating and refining key assumptions adopted in this study, particularly those related to time allocation, maintenance intensity, and labour requirements. Such data would allow for more accurate inventory modelling, reduce uncertainty, and strengthen the robustness of future S-LCA applications.

From an applied perspective, the findings point to several opportunities for mitigating identified social risks. In the WH system, targeted improvements in *occupational health and safety*, such as enhanced training, standardized protective equipment, and improved vessel safety protocols, could directly address the high risks associated with injuries and fatalities. In OC systems, social risk mitigation could focus on reducing the labour intensity of maintenance activities through improved system design, mechanization, or optimized maintenance schedules. Additionally, clearer labour standards, monitoring mechanisms, and governance frameworks could help reduce risks related to forced labour and discrimination in both systems.

Beyond system-specific measures, methodological advancements are also needed to strengthen future social sustainability assessments. While the SHDB provides a valuable screening-level perspective, its reliance on national-level data limits its ability to capture localized social conditions. Integrating SHDB results with site-specific stakeholder data, such as surveys or interviews with workers, operators, and local communities, would enable a more nuanced and context-sensitive assessment of social impacts and enhance the relevance of S-LCA outcomes.

Overall, the results highlight the importance of balancing environmental and social considerations in the development of macroalgae production systems. While WH currently represents the more socially sustainable option, technological, organizational, and governance advancements in OC could progressively reduce its social risks, potentially enabling more equitable and inclusive macroalgae value chains in the future.

## 4. CONCLUSIONS

This study compared the social impacts of WH and OC of *F. lumbricalis* in the Baltic Sea Region using an S-LCA framework. The analysis addresses a key gap in the literature by providing a quantitative social hotspot assessment for macroalgae production systems in Europe.

The results indicate that WH is the more socially sustainable option under the assumptions of this study. The total normalized social impact score for WH was 432.85 Pt, compared to 719.51 Pt for OC, corresponding to an approximately 66 % higher social risk for OC. This ranking proved robust under uncertainty analysis, as Monte Carlo simulations (5000 iterations) showed no overlap between the impact ranges of WH (411.5–454.5 Pt) and OC (678.1–753.3 Pt).

For WH, the harvesting stage was the main contributor (226.85 Pt), with *Injuries & Fatalities*, *Forced Labour*, and *Discrimination* identified as the most relevant risk sub-categories. In the OC scenario, extended boat maintenance dominated the results, leading to higher overall impacts, particularly within the *Labour Rights & Decent Work*, *Community*, and *Society* damage categories.

Overall, WH aligns more effectively with existing socio-economic structures while presenting lower social risks, although improvements in occupational health and safety remain necessary. OC, despite its scalability potential, currently exhibits substantially higher social impacts and would require targeted mitigation measures to improve its social sustainability. These findings highlight the value of integrating quantitative social indicators into decision-making for emerging macroalgae production systems.

## ANNEX

Available: https://zenodo.org/records/18612405

## ACKNOWLEDGEMENT

This research is funded by the Blue Bio ERA-NET Co-Fund project “Total Value Chain Optimization of seaweeds Furcellaria lumbricalis, a bioeconomical ALGAE demonstration (TACO ALGAE)”, project ID No. 36. The people that

contributed to the manuscript with their roles are here listed: Riccardo Paoli: Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis, Data curation, Conceptualization. Joseph Santhi Pechsiri: Writing – review & editing, Methodology, Conceptualization. Alexandre Souza: Writing – review & editing, Methodology, Validation. Francesco Romagnoli: Writing – review & editing, Methodology, Supervision, Funding acquisition.

## DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work the author(s) used OpenAI's ChatGPT and Grammarly, Inc. in order to improve the language and readability of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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