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Cascade Biorefinery of *Furcellaria lumbricalis* Macroalgae: Social Impacts and Integration into a Life Cycle Sustainability Assessment

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***Abstract* – The sustainable valorization of marine biomass is central to advancing a circular bioeconomy. This study delivers the first integrated Life Cycle Sustainability Assessment (LCSA) of a cascade biorefinery for the red macroalga *Furcellaria lumbricalis*, evaluating environmental, economic, and, crucially, social impacts. Addressing the limited attention to social dimensions in macroalgae research, a Social Life Cycle Assessment (S-LCA) was performed using the Reference Scale Approach aligned with ISO 14075:2024 and UNEP guidelines. Stakeholder and expert evaluations were applied to two process phases: harvesting and processing. The S-LCA identified notable social benefits, including strengthened local economic development and improved worker social security, alongside moderate risks in occupational health and safety, as well as wealth distribution. These results were integrated with environmental and economic indicators using a multicriteria decision-making method (TOPSIS), comparing the cascade biorefinery (PrAp) with two alternatives: a single-product system (AAp1) and a three-line extraction system (AAp2). The cascade configuration emerged as the most sustainable option, achieving the highest closeness coefficient (0.776) and demonstrating advantages in product recovery, economic performance, and social co-benefits. Sensitivity analyses confirmed the stability of these rankings under varied weighting assumptions. Overall, this research highlights the value of multi-product valorization strategies and provides new insights to guide sustainable blue bioeconomy development, especially regarding underexplored social aspects.**

***Keywords* – Macroalgae; biorefinery; Life Cycle Sustainability Assessment; social LCA; multi-criteria analysis.**

Nomenclature	
AAp1	Single-product extraction
AAp2	Three-line extraction
AC	Ash content
DW	Dry weight

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GWP	Global warming potential
HCCT	Human carcinogenic and non-carcinogenic toxicity
HS	Health & Safety
IRR	Internal rate of return
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCSA	Life Cycle Sustainability Assessment
LCT	Life Cycle Thinking
LED	Local economic development
NPV	Net present value
Pi	Closeness coefficient
PI	Profitability index
PM	Fine particulate matter
PrAp	Proposed cascade approach
ROI	Return of investment
RS	Reference scale
RSA	Reference scale approach
S-LCA	Social Life Cycle Assessment
TOPSIS	Technique for order preference by similarity to ideal solution
WC	Water consumption
WD	Wealth distribution
WH	Working hours

1. INTRODUCTION

In recent years, the increasing global population and the depletion of virgin resources have underscored the importance of resource recovery from alternative sources [1]. Among these, macroalgae have attracted growing interest due to their rich composition of bioactive compounds, including pigments, proteins, polysaccharides, minerals, and sterols, which can be harnessed through valorization processes [2]. To maximize the potential of macroalgae while minimizing waste generation, the biorefinery concept has been introduced, enabling the extraction of multiple valuable products from biomass in a cascade approach [3]. This approach not only reduces environmental impacts but also contributes to the circular economy by transforming waste streams into valuable products [4]. A cascade biorefinery for macroalgae typically involves sequential stages, including harvesting, pre-processing, extraction of high-value compounds, biomass fractionation, and nutrient and energy recovery [5].

To support the development of a sustainable macroalgae market, the European Commission has established a long-term strategy aimed at stimulating the growth of macroalgae production by addressing current market limitations [6]. In the Baltic Sea Region, *Saccharina latissima* is the predominant commercially cultivated species, while *Furcellaria lumbricalis* is one of the most widely distributed and wild-harvested, especially considering the red macro-family [7].

To date, despite the promising potential of macroalgae-based biorefineries, three major challenges hinder their large-scale industrial application: (i) most research findings are derived from laboratory-scale experiments, with limited information on their feasibility at an industrial scale [8]; (ii) studies have primarily focused on the energy recovery potential of macroalgae, rather than their comprehensive valorization [9]; (iii) when considering the extraction of valuable compounds, research has often focused on a single compound, neglecting the potential for a holistic cascade approach, leading to resource inefficiencies [5], [10]–[12].

To ensure that cascade biorefineries are environmentally, economically, and socially sustainable, Life Cycle Thinking (LCT) provides an integrated framework that considers the entire life cycle of a product or process, from raw material extraction to end-of-life disposal [13]. Comprehensive sustainability assessments according to LCT consider three key dimensions: (i) environmental impacts, analysed through Life Cycle Assessment (LCA); (ii) economic viability is examined using Life Cycle Costing (LCC), and (iii) social implications are evaluated via Social Life Cycle Assessment (S-LCA) [14]–[17].

S-LCA is a methodology designed to assess the social pressures and impacts associated with products and processes [18], [19]. In the context of biorefineries, it evaluates factors such as working conditions, community well-being, social welfare, social responsibility, and equity, helping identify both risks and opportunities [20]. As a result, S-LCA aims to verify the contributions that seaweed valorization technologies have on society, beyond their economic and environmental benefits [21]. Despite its significance, S-LCA remains underrepresented in comparison to environmental and economic sustainability assessments. This can largely be attributed to the recent establishment of standardized guidelines [22], which now offers a more structured and harmonized approach to its application [23], [24]. While several studies have applied S-LCA to biorefineries, these have predominantly focused on the valorization of wood-cellulosic biomass [25], [26]. The application of S-LCA to macroalgae-based biorefineries remains limited, with existing studies geographically concentrated in East and Southeast Asia and primarily focusing on specific macroalgae species [27].

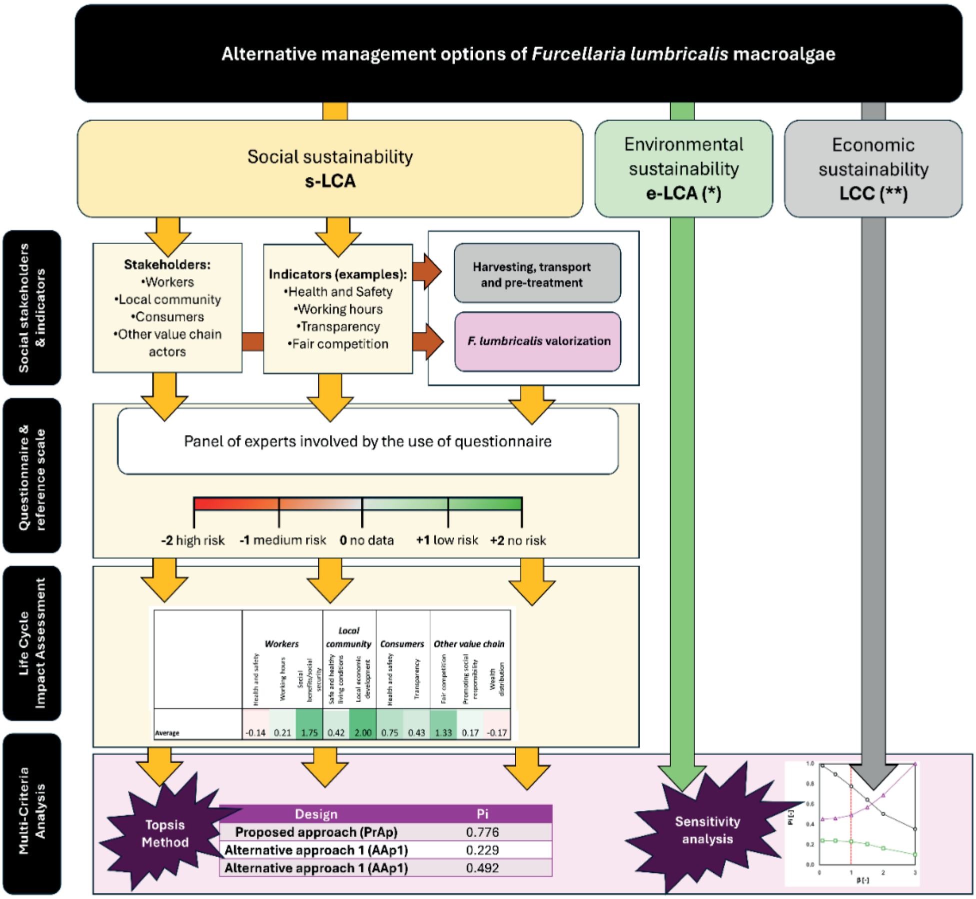
The novelty of this study lies, first, in its in-depth assessment of the potential social impacts associated with an *F. lumbricalis* cascade biorefinery through the application of an S-LCA. Second, by employing a multicriteria approach, the study integrates the social findings with environmental and economic dimensions, delivering a comprehensive Life Cycle Sustainability Assessment (LCSA). The cascade biorefinery concept is benchmarked against single-product and three-line extraction configurations to evaluate relative sustainability performance.

This study contributes to expanding knowledge on the social implications of macroalgae valorization, an aspect often overlooked in traditional impact assessments. By advancing research in sustainable development and resource management, this work provides valuable insights for decision-makers, helping policymakers, industry stakeholders, and researchers in the optimization and implementation of biorefinery technologies for *F. lumbricalis* valorization. To the best of the authors' knowledge, no previous studies have conducted an S-LCA and LCSA of a red macroalgae-based cascade biorefinery, making this research a pioneering effort in the field.

2. MATERIALS AND METHODS

2.1. Overall Methodological Approach

The main objective of this study is to contribute to closing the existing knowledge gap regarding the social dimension of the macroalgae sector, which remains significantly underexplored. Specifically, it aims to identify and assess the key social implications that are most relevant for stakeholders, policymakers, and actors along the macroalgae value chain. In addition, a core aim of this work is to integrate these social aspects with environmental and economic performance indicators to provide a comprehensive perspective on all three pillars of sustainability (Fig. 1).



	Workers			Local community		Consumers		Other value chain		
	Health and safety	Working hours	Social benefits/social security	Safe and healthy living conditions	Local economic development	Health and safety	Transparency	Fair competition	Promoting social responsibility	Wealth distribution
Average	-0.14	0.21	1.75	0.42	2.00	0.75	0.43	1.33	0.17	-0.17

Design	Pi
Proposed approach (PrAp)	0.776
Alternative approach 1 (AAp1)	0.229
Alternative approach 1 (AAp1)	0.492

Fig. 1. Methodological approach used to evaluate the social sustainability of the *F. lumbricalis* biorefinery system and its Life Cycle Sustainability Assessment in comparison with alternative designs. *: data from [5]; **: data from [28].

To achieve this, the study seeks to address the following key research questions:

(i) From a social perspective, how sustainable is the proposed cascade biorefinery for *F. lumbricalis* valorization, and which social aspects are most critical?

(ii) When integrating the social assessment with previously established LCA and LCC results for the same system through the lens of LCSA, does the proposed approach prove to be a more feasible and sustainable solution compared to alternative designs, such as single-product and three-line extraction methods?

To address question (i), an S-LCA was carried out, engaging a diverse group of stakeholders and a panel of experts to ensure a robust evaluation of the social impacts associated with macroalgae biorefinery systems. The outcomes of the social assessment were then combined with environmental and economic indicators within a multicriteria decision-making framework, providing a holistic appraisal of the overall sustainability and practical viability of the cascade biorefinery model to answer question (ii). More details about the methodological implementations are provided in the following sub-chapters.

2.2. Biorefinery Systems Details

The system analysed in this study, developed within the framework of the TACO ALGAE project (Blue Bio CoFund, 2025), encompasses the full value chain of the cascade biorefinery concept, from the harvesting of wild *F. lumbricalis* to the extraction of high-value compounds (i.e., pigments, proteins, and carrageenan), followed by the valorization of residual biomass through biogas production. The system operates at a hybrid scale: industrial for the harvesting phase and laboratory-hypothetical for the biomass processing stage. Specifically, the harvesting process is modelled at an industrial scale, based on an annual maximum collection of 2000 tons of fresh *F. lumbricalis*, in line with the harvesting license currently granted in Estonia, where the biomass is sourced. Conversely, the processing stage remains at a hypothetical scale, as multiple extraction pathways were tested and the one presented here was selected for its high theoretical valorization potential. However, it should be noted that the extraction yields are still based on theoretical values and require future validation through industrial-scale implementation.

2.2.1. Macroalgae harvesting

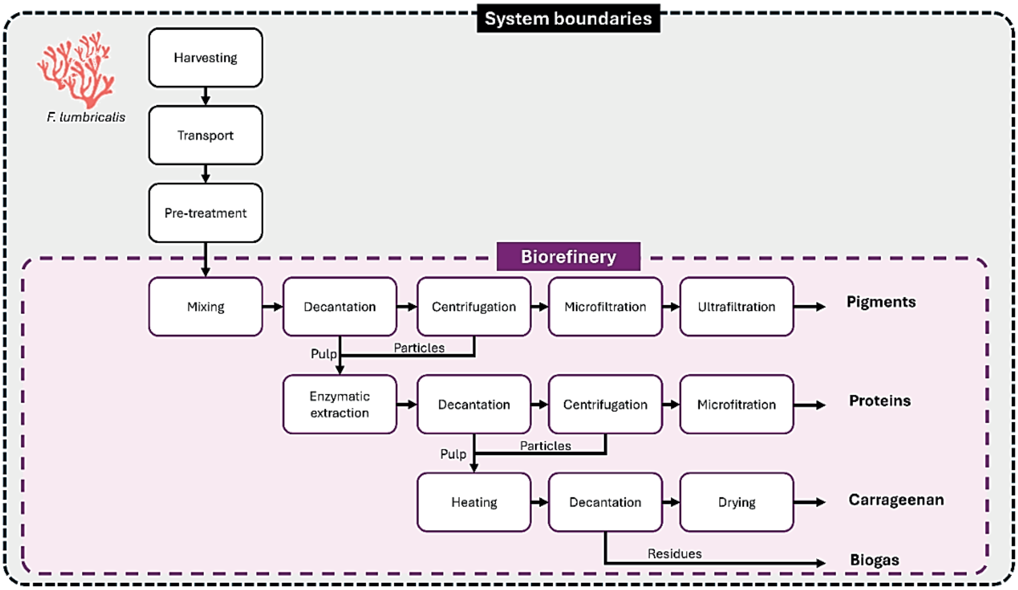


Fig. 2. Technological scheme of the *F. lumbricalis* harvesting, transport, and valorization in the cascade biorefinery (PrAp).

In the first stage of the system (Fig. 2), wild *F. lumbricalis* was harvested in Kassari Bay, Estonia, within a site located 30 to 60 minutes from the mainland. The collection was carried out using trawling boats equipped with nylon nets. After harvesting, the macroalgae were transported 53.2 km to the biorefinery facility using diesel trucks with a 12-ton capacity, ensuring optimized logistics.

To eliminate impurities such as sand and other marine organisms (e.g., shrimps, juvenile fish), the biomass was pre-treated with a washing process, requiring approximately 10 m^3 of water per ton of fresh biomass. Further details on this phase are available in [5].

2.2.2. Macroalgae valorization

The harvested *F. lumbricalis* was valorized in a cascade biorefinery, following the proposed approach (PrAp). In this system, the feedstock follows a continuous flow process, resulting in a multi-product output (Fig. 2).

The valorization process begins with tricanter and centrifuge devices, which separate solid residues (pulp and particles) for subsequent protein extraction, while the remaining liquid fraction undergoes micro- and ultrafiltration for pigment extraction. After pigment extraction, the residual biomass is heated and subjected to enzymatic hydrolysis using the alcalase enzyme and KOH. Following this step, another tricanter and centrifuge process separates the solid fraction for carrageenan extraction, while the remaining liquid fraction is micro- and ultra-filtered for protein extraction.

Subsequently, the protein extraction residues are heated again, and KOH is added. A tricanter then separates the solid fraction from the aqueous phase. The solid residues, from which further value-added extraction is no longer feasible, are repurposed for biogas production, while the aqueous phase is dried to recover carrageenan.

This cascade biorefinery design is set to be able to recover 20 kg of pigments, 100 kg of proteins, and 200 kg of carrageenan from 1 ton of dry *F. lumbricalis*. Additional details on this process are available in [5].

This approach differs significantly from alternative designs tested as benchmarks, namely the single-product extraction approach (AAp1) and the three-line extraction approach (AAp2) (Annexes, Fig. 1 and Fig. 2, respectively). Unlike the PrAp, these alternative methods do not incorporate residue valorization at each stage, resulting in higher volumes of biomass waste that still contain numerous valuable compounds. In AAp1, three separate processing lines are considered, each exclusively dedicated to the production of pigments, proteins, or carrageenan, without utilizing the remaining biomass for further extraction. In contrast, AAp2 assumes that the input biomass is evenly distributed across three independent processing lines, which operate in parallel but without integration or cascading recovery of resources.

2.3. Social Life Cycle Assessment Framework

The S-LCA in this study was conducted using the so-called Reference Scale Approach (RSA), which aligns with the social indicators and stakeholders map outlined in the UNEP Guidelines for Social Life Cycle Assessment [24] and the methodological framework recently formalized in ISO 14075:2024 [22]. This approach employs a reference scale (RS) to convert qualitative responses collected through questionnaires into quantitative scores, enabling the assessment of potential social risks in a structured and comparable manner.

In this way, a two-level investigation was carried out to collect the essential data required for this analysis. The first step involved the selection of the most relevant social impact indicators for the case study (i.e., macroalgae harvesting& cultivation and macroalgae processing). To achieve this, an initial questionnaire was distributed to all members of the

TACO ALGAE project, comprising six partners from six different European countries (Blue Bio CoFund, 2025). The questionnaire categorized stakeholders and included various subcategories of indicators, aligned with the guidelines of [24]. Each stakeholder had the option to select one or more subcategories they considered most relevant (File S1).

Based on the responses from this first questionnaire, a total of ten subcategories and four stakeholder groups were identified as the most significant indicators of social impact for this case study (Table 1). These findings informed the development of a second questionnaire (File S2) to investigate these aspects further.

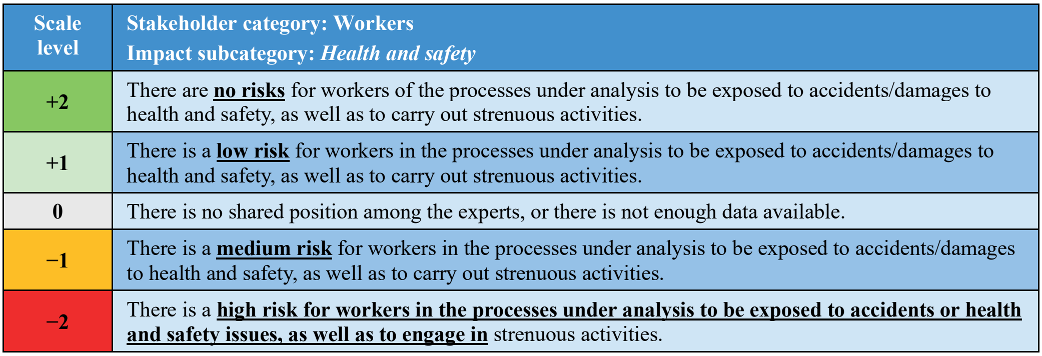
Due to the challenges in directly involving stakeholders, specifically, the only macroalgae producer in Estonia declined to participate in the survey, an expert panel of eight specialists (listed in the annex) was assembled to provide insights. Each panel member received the second questionnaire, along with concise explanatory notes outlining the proposed approach for *F. lumbricalis* valorization. The panel comprised professionals from various academic institutions and industries, carefully selected for their expertise in seaweed management, valorization, and sustainability.

Based on their field experience, each expert was asked to assess the level of risk associated with the various indicators listed in Table 1 for the two main phases of the system: seaweed harvesting & cultivation, and seaweed processing. The experts provided qualitative descriptions of the risks, which were then quantified into a risk level using an RS (detailed in the Annexes). This methodology follows the approach proposed by [30] and aligns with the guidelines outlined in ISO 14075:2024 [22].

TABLE 1. SELECTED INDICATORS TO DEFINE THE POTENTIAL SOCIAL IMPACTS FOR EACH CATEGORY OF STAKEHOLDER

	Categories of stakeholders			
	Workers	Local community	Consumers	Other value chain actors
Indicators of social impact	Health and safety Working hours Social benefits/social security	Safe and healthy living conditions Local economic development	Health and safety Transparency	Fair competition Promoting social responsibility Wealth distribution

An example of RS is reported in Fig. 3 for the indicator *Health and Safety* for the Workers stakeholders.



Scale level	**Stakeholder category: Workers** **Impact subcategory: *Health and safety***
+2	There are **no risks** for workers of the processes under analysis to be exposed to accidents/damages to health and safety, as well as to carry out strenuous activities.
+1	There is a **low risk** for workers in the processes under analysis to be exposed to accidents/damages to health and safety, as well as to carry out strenuous activities.
0	There is no shared position among the experts, or there is not enough data available.
−1	There is a **medium risk** for workers in the processes under analysis to be exposed to accidents/damages to health and safety, as well as to carry out strenuous activities.
−2	There is a **high risk for workers in the processes under analysis to be exposed to accidents or health and safety issues, as well as to engage in** strenuous activities.

Fig. 3. Reference scale for the *Health and Safety* indicator for the Workers stakeholder.

A rating scale from −2 to +2 was applied to each indicator. Negative values (−2 and −1) indicate high and medium levels of social risk, respectively, reflecting potential negative impacts on stakeholders. Positive values (+1 and +2) represent low risk and an absence of risk, respectively, signifying positive social outcomes. When experts did not provide an opinion on a specific indicator, the value "0" was assigned.

For each indicator, the social impact score was determined by calculating the average of the responses from experts who provided an assessment. The overall social impact was then computed as the average social pressure across the two system phases, covering seaweed harvesting&cultivation, as well as seaweed processing.

2.4. Life Cycle Sustainability Assessment framework

LCSA was carried out to determine whether the design of PrAp is sustainable from a fully integrated environmental, economic, and social perspective. A multi-criteria approach was applied using the TOPSIS method [31] on Microsoft Excel, as previously adopted by [32]. The main principle of the TOPSIS method is that the best solution should have the shortest Euclidean distance from the positive ideal alternative and the longest Euclidean distance from the negative ideal alternative [32].

The data for environmental and economic indicators were sourced from [5] and [28], in which an LCA and LCC analysis, respectively, were conducted on the same *F. lumbricalis* cascade biorefinery system, under consistent system boundary conditions. The full data inventories, system modelling details, and sensitivity analyses are thoroughly documented in the aforementioned studies, while the corresponding results are summarized in Tables 1 and 2 of the Annexes. In this context, the present study serves as the final integration step, bringing together previously established environmental and economic assessments with the newly developed social outcomes from the S-LCA. This integration enables the calculation of a comprehensive sustainability index, effectively closing the loop in the life cycle sustainability assessment of the proposed biorefinery model.

For each sustainability dimension, four key indicators were considered:

- *Environmental*: global warming potential (GWP), fine particulate matter formation (PM), human carcinogenic and non-carcinogenic toxicity (HCCT), water consumption (WC). These four were selected as the most representative contributors to the environmental impact of the system. While the original LCA results, based on the ReCiPe 2016 methodology, encompass a broader set of impact categories, only these key indicators were retained to maintain a balanced and comparable structure with the economic and social dimensions in the overall sustainability assessment.
- *Economic*: return of investments (ROI), net present value (NPV), internal rate of return (IRR), and profitability index (PI), as these are the four primary indicators assessed in the LCC analysis.
- *Social*: *health and safety* of the worker (HS); *working hours* (WH); *local economy development* (LED); *wealth distribution* (WD). Chosen for their potential variability across different scenarios.

In the case of S-LCA for AAp1 and AAp2, adjustments were necessary due to differences in system design compared to PrAp.

In AAp2, the HS indicator was assumed to be equal to that of PrAp, while in AAp1, HS was calculated as the sum of the risks associated with the production of each individual product (i.e., single line pigments, proteins, and carrageenan) see Eq. (1) and Eq. (2). Since this configuration is expected to be associated with higher HS risks compared to PrAp, the values were considered negative to reflect the increased level of risk.

$$HS_{\mathrm{AAp1}} = HS_{\mathrm{AAp1,pigments}} - HS_{\mathrm{AAp1,proteins}} - HS_{\mathrm{AAp1,carragenean}} \tag{1}$$

$$HS_{\mathrm{AAp1,pigments}} = HS_{\mathrm{AAp1,proteins}} = HS_{\mathrm{AAp1,carragenean}} = HS_{\mathrm{PrAp}} + \frac{HS_{\mathrm{PrAp}}}{3} \tag{2}$$

In AAp2, the WH was assumed to be the same as in PrAp. However, in AAp1, WH was calculated as the sum of the risks associated with the production of each individual product (Eq. (3) and Eq. (4)). This value was considered negative, as this configuration is assumed to pose a higher WH risk compared to PrAp, following the same approach applied for the HS indicator.

$$WH_{\mathrm{AAp1}} = WH_{\mathrm{AAp1,pigments}} - WH_{\mathrm{AAp1,proteins}} - WH_{\mathrm{AAp1,carragenean}} \tag{3}$$

$$WH_{\mathrm{AAp1,pigments}} = WH_{\mathrm{AAp1,protein}s} = WH_{\mathrm{AAp1,carragenean}} = WH_{\mathrm{PrAp}} \tag{4}$$

LED and WD were calculated based on the total amount of valuable products generated in each scenario, assuming that a higher yield of valuable products leads to greater wealth distribution and lower social risk. Consequently, in AAp1 and AAp2, LED and WD were determined proportionally by comparing the percentage difference in product yield between each system and PrAp. In AAp1, for every 1 ton of dry weight (DW) biomass of *F. lumbricalis* initially processed in each line, 20 kg of pigments, 100 kg of proteins, and 200 kg of carrageenan were obtained, matching the output of PrAp. As a result, LED and WD remained unchanged. In AAp2, for every 1 ton DW of red seaweed introduced into the system, the yield was significantly lower, producing only 6.67 kg of pigments, 33.33 kg of proteins, and 66.67 kg of carrageenan [5]. Therefore, $\mathrm{LED_{AAp2}}$ and $\mathrm{WD_{AAp2}}$ were adjusted accordingly, using Eq. (5) and Eq. (6) to account for these differences in production efficiency.

$$LED_{\mathrm{AAp2}} = \frac{LED_{\mathrm{PrAp}} \cdot \left(pigments_{\mathrm{AAp2}} + proteins_{\mathrm{AAp2}} + carragenaan_{\mathrm{AAp2}} \right)}{\left(pigments_{\mathrm{PrAp}} + proteins_{\mathrm{PrAp}} + carragenaan_{\mathrm{PrAp}} \right)} \tag{5}$$

$$WD_{\mathrm{AAp2}} = WD_{\mathrm{PrAp}} + \frac{WD_{\mathrm{PrAp}}}{3} \tag{6}$$

For $\mathrm{WD_{AAp2}}$, the value was added to $\mathrm{WD_{PrAp}}$ to more accurately represent the increased risk associated with wealth distribution, which arises from the lower product yield in this system design. This adjustment ensures that the negative impact of reduced production is properly reflected in the assessment.

The approach used to determine the weight (*W*) of each criterion, environmental, economic, and social, is detailed in Eq. (7), it is a distributive normalization that provides a structured method for balancing these factors within the overall sustainability evaluation:

$$W = \beta \cdot \frac{1}{n}, \tag{7}$$

where *n* represents the number of criteria considered (i.e., 3 in this study), and β denotes the variation ratio, which was initially set to 1. As a starting point, equal weights were assigned to the three sustainability dimensions, environmental, economic, and social. To evaluate the influence of weighting on the TOPSIS analysis outcomes and, consequently, on the optimal biorefinery design for *F. lumbricalis* valorization, a sensitivity analysis was performed by varying the β value from 0.1 to 3 for each individual criterion. In all scenarios, the *W* of each sustainability pillar was evenly distributed among its respective indicators, ensuring a balanced and consistent assessment framework across all dimensions.

3. RESULTS AND DISCUSSION

3.1. Social Life Cycle Assessment Results

The results of the first questionnaire, which were used to identify the most relevant indicators for this specific case study, are summarized in Table 1. The findings from the second questionnaire, which was administered to the panel of experts to assess the environmental sustainability of the proposed macroalgae supply chain, are reported in Fig. 4. Fig. 5 reports the average risk values.

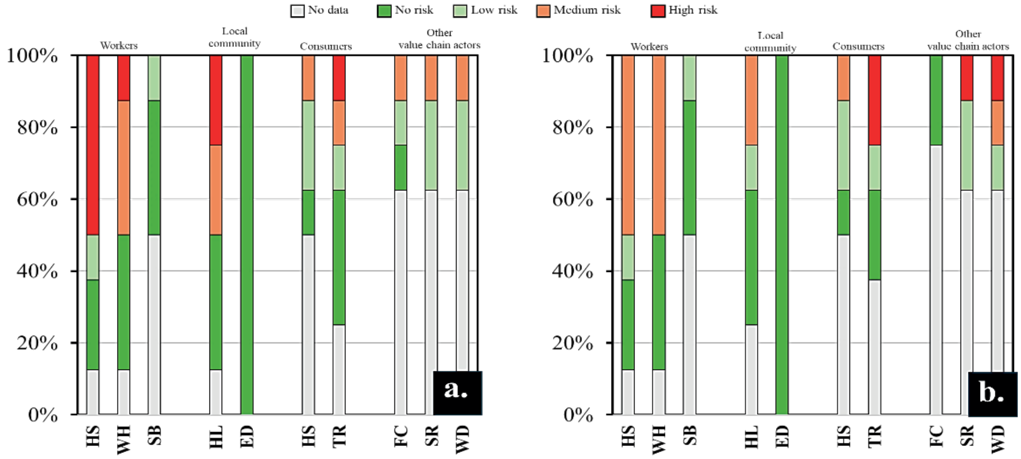
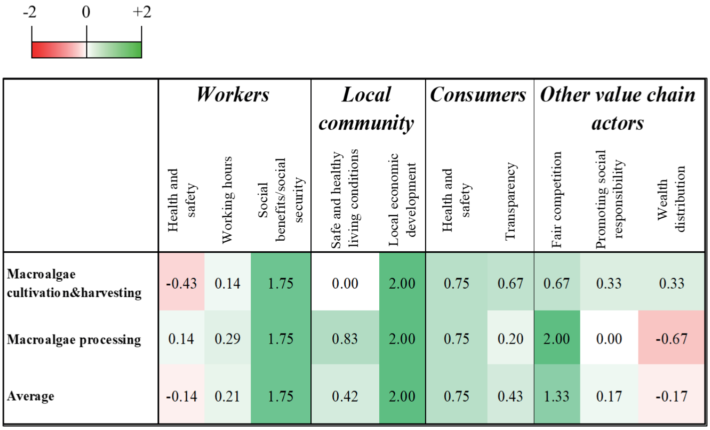


Fig. 4. Answers obtained from the second questionnaire related to the possible social impact of: (a) Macroalgae harvesting & cultivation, (b) Macroalgae processing. HS: *health and safety*; WH: *working hours*; SB: *social benefits/social security*; HL: *Safe and healthy living conditions*; ED: *local economic development*; TR: *transparency*; FC: *fair competition*; SR: *promoting social responsibility*; WD: *wealth distribution*.



	Workers			***Local community***		***Consumers***		***Other value chain actors***		
	Health and safety	Working hours	Social benefits/social security	Safe and healthy living conditions	Local economic development	Health and safety	Transparency	Fair competition	Promoting social responsibility	Wealth distribution
Macroalgae cultivation&harvesting	-0.43	0.14	1.75	0.00	2.00	0.75	0.67	0.67	0.33	0.33
Macroalgae processing	0.14	0.29	1.75	0.83	2.00	0.75	0.20	2.00	0.00	-0.67
Average	-0.14	0.21	1.75	0.42	2.00	0.75	0.43	1.33	0.17	-0.17

Fig. 5. Results of S-LCA.

3.1.1. Macroalgae harvesting & cultivation phases results

The results are shown in Fig. 4a, the analysis reveals notable concerns in specific areas, particularly regarding workers' *Health and safety*, which received an average score of −0.43. This negative rating suggests a moderate level of risk, indicating that worker well-being is compromised and requires urgent attention.

On a more positive note, the local community's *economic development* emerged as a strong area, consistently scoring high with an average of 2.00. This indicates a very low risk and confirms widespread agreement among experts on the significant economic benefits that macroalgae harvesting operations contribute to the local economy.

However, several other aspects present moderate concerns. *Working hours* received an average score of 0.14, reflecting inconsistencies that may require intervention to ensure standardized labour conditions. *Safe and healthy living conditions* within the local community had an average score of 0.00, indicating considerable variability, suggesting that while some communities are benefiting, others face notable challenges that need to be addressed.

Consumers' *health and safety* were assessed with a moderately positive average score of 0.75, implying a generally low risk but also highlighting room for improvement. *Transparency* received an average score of 0.67, indicating an overall low-to-moderate risk. However, the presence of negative responses suggests that transparency measures could be strengthened in certain areas.

The value chain was the stakeholder group with the highest number of null responses, suggesting a lack of expertise in this area, which could limit a comprehensive assessment. *Fair competition* was rated with an average score of 0.67, indicating a low overall risk, though some high-risk responses highlight the need to address disparities in market competition. Similarly, *promoting social responsibility* and *wealth distribution* each scored 0.33, signalling moderate risks and emphasizing the need for stronger efforts to enhance social responsibility practices and tackle economic inequalities.

3.1.2. Macroalgae processing phase results

For these operations, the results are reported in Fig. 4(b).

Within the workers category, the *health and safety* indicator received an average score of 0.14, indicating a moderate risk. While some areas demonstrate satisfactory conditions, concerns remain that require attention to improve the workers' well-being. However, this score is notably lower compared to the macroalgae harvesting stage, suggesting that harvesting poses a greater occupational hazard. The *working hours* indicator scored an average of 0.29, reflecting similar moderate risks, with inconsistencies in work schedules that may require corrective actions to ensure standardization across the industry. In contrast, the *social benefits/social security* indicator achieved a high positive average of 1.75, signifying low risk and suggesting that workers generally have reliable access to these benefits.

In the local community category, the *safe and healthy living conditions* indicator received an average score of 0.83, reflecting a lower level of risk and generally satisfactory conditions, though some areas may still require further attention. Meanwhile, the *local economic development* indicator remained consistently high at 2.00, indicating very low risk and robust economic contributions from the seaweed processing industry.

For consumers, the *health and Safety* indicator recorded a positive average score of 0.75, signifying a low risk in this category. However, the presence of a negative score highlights the need for ongoing improvements to maintain high safety standards. The *transparency* indicator had an average score of 0.20, reflecting a moderate risk. Negative responses suggest that transparency practices could be significantly improved to strengthen consumer trust and confidence in the sector.

In the value chain category, the *fair competition* indicator received a strong positive score of 2.00, indicating minimal risk and a well-functioning competitive market. However, the *promoting social responsibility* indicator scored 0.00, suggesting a neutral risk level. While some efforts to encourage social responsibility exist, they are not widespread, indicating room for improvement. The *wealth distribution* indicator, however, recorded a negative average score of −0.67, pointing to a moderate to high risk. This suggests that economic disparities remain significant, requiring targeted measures to promote more equitable wealth distribution within the industry.

3.1.3. S-LCA take-home messages

Based on the findings, experts consistently identified no risk for the *local economic development* indicator, assigning a score of +2 for both the harvesting & cultivation and processing phases. This positive outcome reflects the potential of macroalgae activities to stimulate local infrastructure development, support ancillary services, and contribute to local economies through employment opportunities. In small and remote locations, such as islands, macroalgae-related jobs may represent one of the few viable sources of income, helping to sustain economic activity even during off-seasons when harvesting operations are limited.

A similarly positive trend was observed for the *social benefits/social security* indicator, which received an average score of +1.75. However, only half of the surveyed experts provided input for this indicator, introducing a degree of uncertainty. Concerns were raised regarding the seasonal nature of macroalgae harvesting, as temporary workers may not receive the same level of social protection as permanent employees, potentially leading to inequalities in access to social benefits.

For the *fair competition* indicator, no risk was identified during the processing phase, while a low level of risk emerged during biomass preparation. Moderate risks were instead detected for worker *health and safety* during the harvesting and cultivation phase (−0.43) and for *wealth distribution* in the processing phase (−0.67). Occupational risks in harvesting activities are primarily associated with offshore operations, where exposure to unpredictable weather conditions, machinery failures, and short operational windows increases the likelihood of accidents. The physically demanding nature of the work may also result in long-term health impacts, particularly musculoskeletal disorders. The adoption of mechanized solutions, such as electric loaders, could mitigate these risks by reducing manual handling. In processing facilities, hazards are mainly related to cutting and milling equipment and potential chemical exposure, underscoring the need for adequate training and protective measures.

Regarding *wealth distribution*, the results suggest a potential imbalance in how economic benefits are shared across the value chain, raising concerns that profits generated by the biorefinery may disproportionately favour specific actors rather than being equitably distributed among stakeholders.

For the *safe and healthy living conditions* indicator, macroalgae-related activities were generally perceived as posing lower risks than other aquaculture operations, such as fish or mussel farming, which may contribute to nutrient accumulation and ecosystem disturbances. Nevertheless, intensive harvesting using diesel-powered vessels can introduce oil residues and polycyclic aromatic hydrocarbons into the marine environment, potentially affecting local ecosystems and communities. Additional risks may arise from the use of antifouling agents on boats, which can leach into surrounding waters.

The *transparency* indicator highlighted concerns related to misleading or insufficiently substantiated claims about the climate benefits of macroalgae biomass. Such claims are often used in marketing without robust scientific evidence, increasing the risk of consumer misinformation. To address this issue, publicly available and scientifically validated data on biomass composition and environmental performance should be provided.

A key limitation of the social assessment is the limited engagement of "other value chain actors," as reflected by the high proportion of missing responses for this stakeholder group. This gap indicates the need for future studies to strengthen stakeholder involvement, particularly for indicators such as *fair competition*, *social responsibility*, and *wealth distribution*. Despite these limitations, the social mapping performed provides meaningful preliminary insights and establishes a solid basis for more comprehensive social sustainability assessments in future macroalgae biorefinery research.

3.2. Life Cycle Sustainability Assessment Results

The TOPSIS methodology was applied to calculate the final LCSA and determine the most sustainable biorefinery design for the valorization of *F. lumbricalis* among the three proposed configurations: PrAp, AAp1, and AAp2. The first step in the TOPSIS approach involved defining whether each selected indicator within the three sustainability dimensions (environmental, economic, and social) should be maximized or minimized in comparison to an ideal scenario. This classification ensures that sustainability performance is assessed consistently across all criteria. The details of this step are presented in Table 2.

TABLE 2. INDICATORS AND CRITERIA DECISION

Dimension	Indicator	Unit	Type	MIN/MAX
Environmental	Global warming potential	kg CO_2 eq.	Quantitative	MIN
	Fine particulate matter formation	kg PM2.5	Quantitative	MIN
	Human carcinogenic and non-carcinogenic toxicity	kg 1.4-DCB	Quantitative	MIN
	Water consumption	m^3	Quantitative	MIN
Economic	Return of investment	%	Quantitative	MAX
	Net present value	EUR	Quantitative	MAX
	Internal rate of return	%	Quantitative	MAX
	Profitability index	–	Quantitative	MAX
Social	*Health & safety of the worker*	–	Semi-quantitative	MAX
	Working hours	–	Semi-quantitative	MAX
	Local economy development	–	Semi-quantitative	MAX
	Wealth distribution	–	Semi-quantitative	MAX

Note: Min and Max indicate whether each indicator has been minimized or maximized, respectively, compared to an ideal scenario. The data for the LCA and LCC refer to 2022 and 2024 respectively.

Keeping these criteria selections in mind, a normalization matrix was constructed for the three scenarios (PrAp, AAp1, and AAp2). This matrix ensures that all indicators are scaled appropriately and is reported in Table 3.

TABLE 3. NORMALIZED MATRIX FOR THE ASSESSMENT INDICATORS AND THE DIFFERENT BIOREFINERY DESIGNS

Dimension	Indicator	Unit	Scenarios		
			PrAp	AAp1	AAp2
Environmental	GWP	kg CO_2 eq.	0.68	0.69	0.23
	PM	kg PM2.5	0.54	0.80	0.27
	HCCT	kg 1.4-DCB	0.49	0.83	0.28
	WC	m^3	0.74	0.63	0.21
Economic	ROI	%	1.00	−0.07	−0.09
	NPV	EUR	0.99	−0.09	−0.05
	IRR	%	0.78	0.62	0.00
	PI	–	0.99	−0.09	−0.05
Social	HS	–	0.51	−0.69	0.51
	WH	–	0.58	−0.58	0.58
	LED	–	0.69	0.69	0.23
	WD	–	−0.52	−0.52	−0.69

Finally, the normalized matrix was weighted, and the Euclidean distance from both the ideal and worst-case scenarios was calculated to determine the most sustainable biorefinery design among the three proposed configurations. Fig. 6 provides a visual representation of the results, illustrating the comparative sustainability performance of PrAp, AAp1, and AAp2.

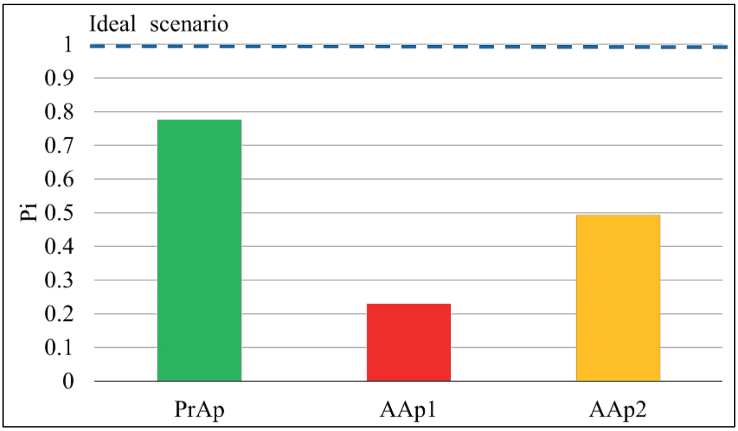


Fig. 6. Results of the LCSA following the multicriteria approach with TOPSIS. *Pi*: closeness coefficient.

The PrAp configuration emerged as the most sustainable design for the *F. lumbricalis* biorefinery, achieving a closeness coefficient (*Pi*) of 0.776, indicating the shortest distance to the ideal scenario (*Pi* = 1). In comparison, AAp2 scored a *Pi* value of 0.492, ranking as the intermediate option, while AAp1, with a *Pi* value of 0.229, was identified as the least sustainable configuration, highlighting the limitations of a single-product extraction approach.

To ensure the robustness of these results, a sensitivity analysis was conducted by applying varying weights to the three sustainability dimensions: environmental, economic, and social.

This analysis allowed for the examination of how shifting the emphasis among these dimensions influences the overall sustainability ranking of each design. The outcomes of the sensitivity analysis are illustrated in Fig. 7. This approach provides a clearer understanding of the trade-offs and critical factors in each scenario, enabling a more nuanced interpretation of sustainability when viewed from different stakeholder or policy priorities.

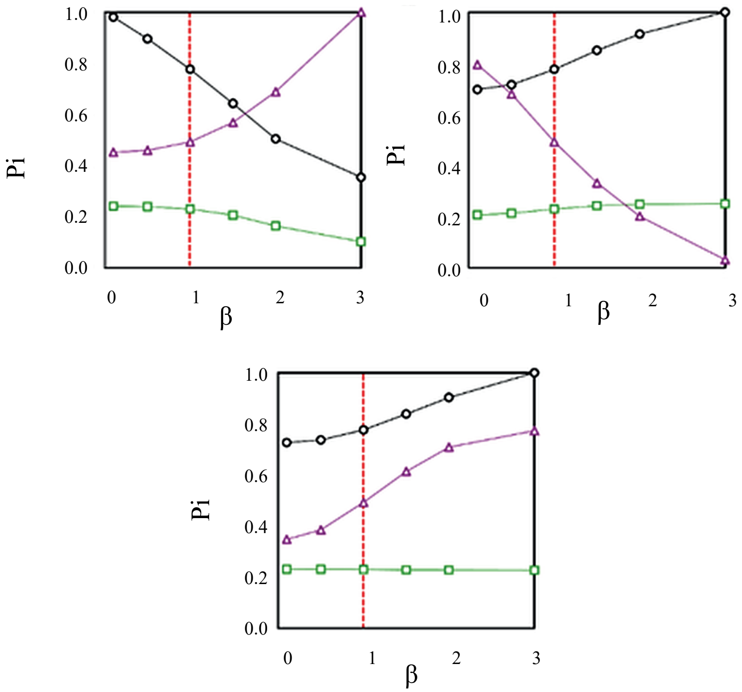


Fig. 7. Results of the sensitivity analysis for weights to: (a) environmental, (b) economic, and (c) social criteria. Closeness coefficient (Pi) as a function of the variation ratio (β). The black line represents the PrAp, the violet line AAp2, and the green line AAp1. The Red dashed line indicates the results of the LCSA before the sensitivity analysis.

In general, even when considering the sensitivity analysis, PrAp remains the most sustainable design. Across 15 simulations, it was identified as the most sustainable scenario in 80 % of the cases. The most critical dimension affecting the ranking of the PrAp scenario is the environmental aspect, where AAp1 outperforms PrAp in two cases when the environmental weight is highest. This outcome highlights the importance of giving greater attention to environmental sustainability in the future development of *F. lumbricalis* biorefineries. From an economic perspective, the cascade approach (PrAp) proves to be advantageous, as the ability to generate multiple products strengthens market positioning and enhances economic feasibility. However, AAp2 faces significant challenges in this regard. Due to the initial biomass split, AAp2 is unable to achieve the same product yield extraction as PrAp, making it economically unviable. In fact, when the economic weight is highest, AAp2 drops below AAp1, further emphasizing its limitations. Regarding the social dimension, no crossing points were observed between scenarios. This is likely due to the semi-quantitative nature of the input values, which limits the ability to differentiate the designs significantly in social terms. Table 4 summarizes the probability of ranking for each scenario across the sensitivity analysis simulations.

TABLE 4. PROBABILITY RANKING OF THE DIFFERENT DESIGN APPROACHES

	Probability ranking		
Design	**Best scenario**	**Mid scenario**	**Worst scenario**
PrAp	80 %	20 %	0 %
AAp1	0 %	47 %	53 %
AAp2	20 %	33 %	47 %

3.2.1. LCSA discussion

The integration of the three sustainability pillars through the LCSA framework, using the TOPSIS method, proved to be an effective approach for generating a holistic sustainability index. The results demonstrated that the cascade biorefinery design (PrAp) offers the most favorable balance among environmental, economic, and social performance. While PrAp showed slightly higher environmental impacts compared to AAp2, it achieved superior overall sustainability due to its strong economic returns and notable social benefits, such as job creation and support for local development. These findings reinforce the strategic importance of adopting a circular, multi-product valorization approach for the development of a sustainable blue bioeconomy centered on *F. lumbricalis*. Although the cascade configuration is more complex and resource-intensive to implement, it delivers substantial gains across all dimensions of sustainability compared to the more linear, single-product alternatives.

A particularly critical aspect of the PrAp design remains its environmental performance, especially concerning the high energy consumption required for extraction processes, which is the main contributor to environmental impacts. This highlights the need for future research and development efforts to focus on improving energy efficiency or integrating renewable energy sources into the process. From an economic perspective, the prioritization of full biomass valorization has proven to be a sound strategy, as this design choice significantly enhances the sustainability profile of PrAp in the overall LCSA evaluation.

Nonetheless, certain limitations must be acknowledged. The use of the TOPSIS method, while appropriate for this analysis, represents only one possible multi-criteria decision-making approach. Future studies should consider exploring alternative methodologies, such as value or utility-based models (e.g., MAVT, MAUT, SAW), pairwise comparison techniques (e.g., AHP, ANP), or outranking methods (e.g., PROMETHEE, ELECTRE), to examine how methodological choices may influence the ranking of sustainability outcomes. Furthermore, the study relies on a pre-industrial system model, which incorporates theoretical extraction yields and a combination of primary, proxy, and literature-based data, introducing a level of uncertainty. As the biorefinery concept evolves, future research should aim to refine data inputs through pilot or industrial-scale validation.

Another current constraint is the lack of integrated LCSA studies on comparable biorefinery systems based on conventional feedstocks (e.g., terrestrial crops), which limits the possibility of benchmarking the full sustainability profile of the cascade seaweed biorefinery. While isolated comparisons of environmental, economic, or social indicators are more feasible, comprehensive LCSA benchmarking is hindered by inconsistencies in system boundaries, economic parameters, and social impact definitions. To overcome this, future research should aim to develop a harmonized methodological framework with standardized system boundaries, data requirements, and impact metrics to support meaningful cross-system comparisons.

Despite these limitations, this study marks a pioneering contribution toward advancing a sustainable blue bioeconomy. It demonstrates the viability and necessity of multi-product, circular biorefinery designs for the valorization of *F. lumbricalis* and offers a strong foundation for future research, policy development, and industrial implementation aimed at achieving long-term sustainability in the macroalgae sector.

3.3. Future Perspective

The findings of this study confirm the sustainability potential of a cascade biorefinery approach for *F. lumbricalis*; however, several critical pathways must be addressed to support its transition from conceptual design to industrial implementation. A first and necessary step is moving beyond laboratory-scale assumptions toward pilot-scale validation. Pilot projects are essential to confirm extraction yields, process reliability, and scalability under real operating conditions. They would also generate empirical data on supply chain logistics, labor requirements, and site-specific constraints, which are currently approximated. In line with the EU Blue Bioeconomy Strategy, such demonstration activities are crucial to de-risk innovative bio-based value chains and accelerate their market uptake. Collaboration between academic institutions, industry stakeholders, and technology providers will be instrumental in this phase to ensure technical robustness and contextual adaptability.

The long-term viability of macroalgae-based biorefineries is also closely linked to realistic and market-oriented product strategies. While cascade processing improves resource efficiency, economic feasibility ultimately depends on the demand for the resulting products. Future efforts should therefore prioritize improving product purity, meeting food and pharmaceutical safety standards, and ensuring compliance with evolving EU regulatory frameworks. Expanding toward higher-value applications such as nutraceuticals, cosmetics, and biostimulants could enhance economic resilience and align with EU policy objectives aimed at fostering high-value bio-based products. At the same time, the co-development of product standards, certification schemes, and traceability systems would strengthen consumer trust and reduce the risk of misleading sustainability claims, an issue highlighted by the S-LCA results.

Targeted policy interventions represent a key enabler for unlocking the full potential of macroalgae valorization. National and EU-level instruments, including dedicated funding schemes, tax incentives, and simplified permitting procedures, can significantly reduce barriers to entry for algae-based biorefineries. Clear regulatory pathways for novel macroalgae-derived products, particularly in food, feed, and pharmaceutical applications, would reduce market uncertainty and attract private investment. Moreover, policies promoting industrial symbiosis, fair labor practices, and environmental protection are essential to ensure that biorefinery systems align not only with climate and resource-efficiency goals but also with the social sustainability objectives of the European Green Deal [33] and Circular Economy Action Plan [34].

Given the diversity of macroalgae species and regional biomass characteristics, the LCSA framework developed in this study should be extended to other species and geographic contexts. Comparative applications across different cultivation systems, processing routes, and socio-economic settings would support evidence-based policy development and help identify best practices for sustainable blue bioeconomy deployment. Integrating cascade biorefineries into broader circular systems, such as co-location with aquaculture, wastewater treatment, or greenhouse agriculture, offers additional opportunities for nutrient recovery, energy integration, and infrastructure sharing, consistent with ambitious closed-loop bio-based systems.

Investment in human capital will also be a critical success factor. Workforce training, vocational education, and interdisciplinary programs are needed to build the technical and managerial skills required to operate advanced biorefinery systems. Knowledge-sharing platforms and cross-sector networks, as encouraged by EU innovation and skills agendas [35], can further support technology transfer and dissemination of best practices.

Ultimately, the most decisive next step lies in strengthening demand-side analysis for cascade biorefinery outputs. Without verified market demand, even processes that perform well environmentally and socially may remain economically unviable. Future research should therefore bridge technological development with market analysis, stakeholder engagement, and policy foresight to ensure that macroalgae-based biorefineries can contribute meaningfully to the EU Blue Bioeconomy and Circular Economy objectives.

4. CONCLUSIONS

This study presents the first fully integrated LCSA of a *F. lumbricalis* cascade biorefinery, simultaneously evaluating environmental, economic, and social dimensions through the combined application of LCA, LCC, and S-LCA. By comparing a cascade biorefinery configuration with alternative single-product and three-line extraction designs, the results demonstrate that the cascade approach delivers the most balanced sustainability performance, enhancing resource efficiency, improving economic outcomes under favourable market conditions, and generating positive social contributions such as employment opportunities and local economic development.

A key novel contribution of this research lies in the explicit integration of S-LCA into the sustainability evaluation of *F. lumbricalis* valorization. While previous studies on macroalgae biorefineries have predominantly focused on environmental and techno-economic aspects, social implications have remained largely unaddressed. The S-LCA results provide new insights into critical social hotspots, including occupational *health and safety*, *wealth distribution* along the value chain, and community-level impacts, highlighting the importance of incorporating social criteria in biorefinery design and decision-making.

By embedding S-LCA within an LCSA framework, this study advances beyond existing macroalgae assessments by offering a complete and structured sustainability evaluation tailored to a red macroalga species under Baltic Sea Region conditions. The findings indicate that multi-product cascade biorefineries represent a promising pathway for advancing the blue bioeconomy, reducing biomass losses, and maximizing value generation, provided that economic, technological, and social challenges are carefully managed. Overall, this work establishes a methodological and empirical foundation for future research and supports the development of socially, environmentally, and economically sustainable macroalgae-based biorefineries.

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ANNEX

Available: https://zenodo.org/records/18361385

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