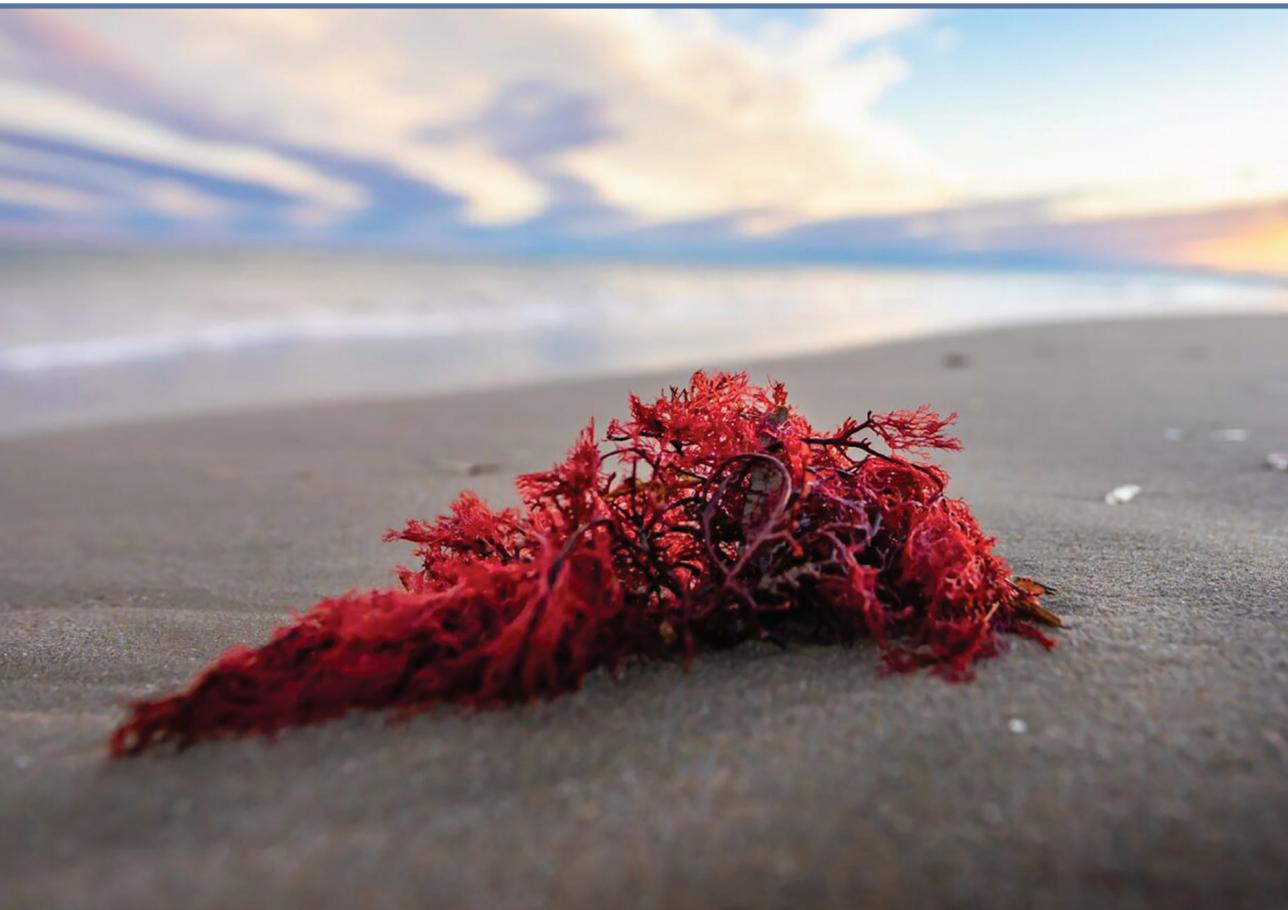


Riccardo Paoli

**NOVEL CASCADE BIOREFINERY CONCEPT FOR
FURCELLARIA LUMBRICALIS: A LIFE CYCLE
SUSTAINABILITY ASSESSMENT-BASED STUDY**

Summary of the Doctoral Thesis



RIGA TECHNICAL UNIVERSITY

Faculty of Natural Sciences and Technology
Institute of Energy Systems and Environment

Riccardo Paoli

Doctoral Student of the Study Programme “Environmental Engineering”

**A NOVEL CASCADE BIOREFINERY CONCEPT
FOR *FURCELLARIA LUMBRICALIS*: A LIFE
CYCLE SUSTAINABILITY ASSESSMENT-
BASED STUDY**

Summary of the Doctoral Thesis

Scientific supervisors:

Professor Dr. sc. ing.

FRANCESCO ROMAGNOLI

Assistant Professor Dr. sc. ing.

MAKSIMS FEOFILOVŠ

RTU Press

Riga 2025

Paoli, R. A Novel Cascade Biorefinery Concept for *Furcellaria Lumbricalis*: A Life Cycle Sustainability Assessment-Based Study. Riga: RTU Press, 2025. 80 p.

Published in accordance with the decision of the Promotion Council “RTU P-19” of 24 April 2025, Minutes No. 225.

Cover picture from “TACO Algae” project.

<https://doi.org/10.7250/9789934372056>
ISBN 978-9934-37-205-6 (pdf)

DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (Ph.D.), the present Doctoral Thesis has been submitted for defence at the open meeting of RTU Promotion Council on 11 September 2025 at 14.00 at the Faculty of Natural Sciences and Technology of Riga Technical University, Āzenes iela 12/1, Room 607.

OFFICIAL REVIEWERS

Professor Dr. sc. ing. Elisabetta Palumbo
University of Bergamo, Italy

Professor Dr. sc. ing. Timo Laukkanen
Aalto University, Finland

Professor Dr. sc. ing. Anna Kubule
Riga Technical University

DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for review to Riga Technical University for promotion to the scientific degree of Doctor of Science (Ph.D.) is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for promotion to a scientific degree.

Riccardo Paoli (signature)

Date:

The Doctoral Thesis has been written in English. It consists of an Introduction, three chapters, Conclusions, 57 figures, 50 tables, and two appendices; the total number of pages is 185. The Bibliography contains 235 titles.

TABLE OF CONTENTS

Introduction.....	5
Objective and tasks of the Doctoral Thesis.....	6
Hypothesis of the Thesis.....	7
Scientific significance of the Doctoral Thesis.....	7
Practical significance of the Doctoral Thesis.....	8
Research methodology.....	9
Approbation of the research results.....	10
Other scientific publications.....	11
Reports at scientific conferences.....	12
Structure of the Doctoral Thesis.....	12
1. State-of-the-art analysis.....	14
1.1. The macroalgae biorefinery system.....	14
1.2. Take-home messages.....	18
2. Methodology.....	21
2.1. The technological designs for the <i>F.lumbricalis</i> biorefinery.....	21
2.2. The environmental life cycle assessment.....	26
2.3. The life cycle costing.....	35
2.4. The social life cycle assessment.....	39
2.5. The life cycle sustainability assessment.....	46
3. Results and discussion.....	48
3.1. Environmental results.....	48
3.2. Economic results.....	56
3.3. Social results.....	61
3.4. Final sustainability index.....	68
Conclusions and recommendations.....	72
References.....	76

INTRODUCTION

Macroalgae are increasingly recognized as a versatile and sustainable resource within the bio-based economy, owing to their unique characteristics and rapid growth potential. These marine organisms represent the fastest-growing biomass [1] and play crucial ecological roles in marine ecosystems, including the absorption of dissolved nutrients [2] and their function as habitat-structuring species [3]. Furthermore, macroalgae contribute to coastal protection by mitigating the impact of hazardous waves [4] and play a significant role in carbon sequestration [5].

The biochemical composition of macroalgae is particularly diverse, encompassing a wide array of bioactive compounds such as phytopigments (e.g., carotenoids), polyunsaturated fatty acids, phenolic compounds, tannins, peptides, lipids, enzymes, vitamins, carbohydrates, and terpenoids [6]. Notably, these compounds are often more readily accessible than those found in terrestrial biomass, primarily due to the lower lignin content of macroalgae [7].

These distinctive properties have facilitated the integration of macroalgae into various commercial applications. In Europe, in particular, these applications have been further supported by policies aimed at promoting a sustainable economy, particularly within the framework of the European Commission's Green Deal [8]. The Deal's objectives, achieving climate neutrality, preserving biodiversity, and advancing sustainable food production by 2050, highlight the critical role of macroalgae-based biorefineries. A key milestone in this context is the adoption of the EU Algae Initiative [9] in 2022, which sets out a strategic framework of 23 targeted actions aimed at enhancing algae production, streamlining regulatory processes, and increasing public awareness of its benefits. Complementing this initiative, the EU4Algae Platform [10] serves as an interactive hub, fostering collaboration and knowledge exchange within the European algae industry. Further contributions have been made by the Joint Research Centre, which has established guidelines for sustainable European seaweed aquaculture [11], aiming to meet the growing global demand for biomass while ensuring environmental sustainability.

Despite the regulatory progress, fully unlocking the potential of macroalgae necessitates the development of standardized processes across all operational stages, from biomass cultivation or harvesting to chemical extraction, within the biorefinery framework [12]. Several challenges must be addressed before macroalgae biorefineries can achieve full-scale implementation. Currently, research and commercial initiatives remain in the developmental phase, predominantly focusing on single-product extractions while lacking comprehensive studies that facilitate the transition to large-scale applications [13]. The majority of studies have primarily examined the energy recovery potential of macroalgae, rather than a holistic valorization approach. The unique composition of macroalgae requires tailored processing techniques distinct from those applied to traditional lignocellulosic biomass [14]. Presently, research efforts are primarily centered on refining extraction methodologies rather than addressing practical market implementation and sustainability quantifications. While environmental and economic analyses have begun to raise awareness in recent years, social implications remain largely unexplored. This highlights the need for a truly sustainable approach that integrates,

with a balanced tackle, all three pillars of sustainability: environmental, economic, and social [15]. The life cycle thinking (LCT) approach provides a comprehensive framework for assessing sustainability by considering the entire life cycle of a product or process, from raw material extraction to end-of-life disposal [16].

This Thesis, therefore, focuses on defining a life cycle sustainability assessment (LCSA) for a novel cascade biorefinery based on the red macroalga *Furcellaria lumbricalis*, which is abundantly available in the Baltic Sea region [17]. The LCSA integrates environmental life cycle assessment (LCA), life cycle costing (LCC), and social life cycle assessment (S-LCA) to provide a complete evaluation of the sustainability of macroalgae-based biorefinery systems.

Objective and tasks of the Doctoral Thesis

The objective of this Thesis is to evaluate the sustainability of a cascade biorefinery utilizing the red macroalgae *F. lumbricalis* through a quantitative LCSA. The defined system aims to recover valuable compounds such as pigments, proteins, and carrageenan, while also valorizing the residual biomass. To achieve this overarching goal, the research is structured around the following key questions:

- What is the current state of macroalgae biorefineries?

This objective seeks to assess and define the latest advancements in macroalgae-based biorefineries, highlighting key challenges and opportunities in the field.

- What are the possible designs for an *F. lumbricalis* biorefinery?

This involves developing a tailored cascade biorefinery model for *F. lumbricalis*, with the aim of maximizing biomass valorization from a sustainability perspective. Additionally, this model will be compared to alternative benchmark biorefinery designs identified in the state-of-the-art analysis.

- What is the environmental footprint of the *F. lumbricalis* biorefinery system?

To quantify the environmental impact of the designed biorefinery, an LCA will be conducted, identifying critical processes and parameters that must be addressed to ensure environmental sustainability.

- What is the economic feasibility of the *F. lumbricalis* biorefinery?

An LCC analysis will be performed to assess the financial viability of the system and evaluate its economic sustainability.

- What are the social implications of implementing an *F. lumbricalis* biorefinery?

An S-LCA will be conducted to analyze the social impacts associated with the biorefinery, considering different scales of implementation within the macroalgae value chain.

- Is the cascade biorefinery the most sustainable approach for *F. lumbricalis* valorization?

The final step involves integrating LCA, LCC, and S-LCA results into a comprehensive sustainability index to determine the most sustainable biorefinery design for *F. lumbricalis*.

Hypothesis of the Doctoral Thesis

The hypothesis underlying this Thesis is as follows:

*The development of a cascade biorefinery approach specifically tailored for the red macroalgae *F. lumbricalis* enables a sustainable, circular, and efficient utilization of biomass, ensuring environmental benefits, economic viability, and increased social awareness when compared with other designs.*

This hypothesis will be tested through a comprehensive evaluation of the proposed cascade biorefinery model, assessing its performance in comparison to alternative biorefinery designs. The benchmarking process will incorporate environmental, economic, and social sustainability criteria, ensuring a complete assessment of its advantages and limitations. By integrating insights from LCA, LCC, and S-LCA, this research aims to provide a quantitative and multidisciplinary perspective on the feasibility and impact of macroalgae-based biorefineries in the bioeconomy.

Scientific significance of the Doctoral Thesis

Marine biomass, particularly macroalgae, presents a promising yet fully underutilized resource for sustainable biorefinery applications. However, challenges remain in ensuring that such systems are environmentally sound, economically viable, and socially responsible.

This doctoral research positions itself at the intersection of bioresource valorization, LCSA, and circular bioeconomy principles, offering a comprehensive evaluation of a cascade biorefinery approach for the red macroalga *F. lumbricalis* in the Baltic Sea Region. By integrating a complete sustainability assessment, this study contributes to advancing macroalgae-based biorefineries as a key component of future sustainable bioeconomic strategies.

The urgent need for standardized sustainability assessments in the biorefinery sector underscores the scientific relevance of this research. While macroalgae-based biorefineries have been explored primarily from a technological perspective, there remains a critical gap in assessing their environmental, economic, and social sustainability through a quantitative, life-cycle-based framework. Moreover, European policies emphasize the necessity of establishing sustainable and scalable macroalgae-based industries. However, current methodologies lack a unified approach to evaluating sustainability comprehensively. This doctoral study contributes to the scientific advancement of macroalgae biorefineries in three innovative ways:

1. Integrated sustainability. This research includes the three sustainability pillars (i.e., environmental, economic, and social) through a quantitative LCSA tailored to a Baltic Sea Region scenario. By combining LCA, LCC, and S-LCA, it provides a robust framework for evaluating macroalgae biorefineries beyond conventional environmental impact analyses.
2. Innovation in S-LCA. The study advances S-LCA methodologies, particularly in the macroalgae sector, where social impacts remain largely unexplored. By investigating the socio-economic implications of macroalgae-based biorefineries at different scales, this research enhances understanding of their potential role in

coastal community development, job creation, and stakeholder engagement, for example.

3. Collaboration impact. This Thesis, as part of the European project TACO ALGAE [18], strengthens multidisciplinary collaborations between research institutions, universities, and industry partners, facilitating knowledge exchange and practical implementation of sustainable biorefinery concepts. Through industry partnerships, it fosters the development of real-world applications that align with European sustainability policies and bioeconomic strategies.

The concepts and outcomes developed and applied in the Thesis have been discussed in peer-reviewed scientific papers and presented at international conferences, highlighting their scientific innovation and significance.

Practical significance of the Doctoral Thesis

The findings of this doctoral research are of critical importance to stakeholders in the macroalgae sector, including industry professionals, policymakers, and researchers working towards sustainable bioeconomic solutions.

As the global demand for renewable biomass resources grows, macroalgae biorefineries have the potential to offer environmentally friendly, economically feasible, and socially responsible alternatives to traditional biomass processing. However, their large-scale implementation remains hindered by technical, economic, and regulatory challenges. This research provides a structured approach to overcoming these challenges by integrating LCSA into cascade biorefinery designs.

By applying an integrated sustainability framework, the study delivers quantitative insights that inform decision-making across the macroalgae industry, policy landscape, and academia.

The practical relevance of this research is particularly reflected in three key areas:

1. Industry application. The study delivers technical insights that are directly applicable to macroalgae-sector stakeholders, including biorefinery operators, investors, and policymakers. By evaluating various biorefinery designs, this research provides a benchmark for best practices, guiding stakeholders in selecting the most efficient, sustainable, and scalable approaches for *F. lumbricalis* valorization.
2. Feasibility analysis. The research identifies the key challenges affecting the environmental and economic viability of macroalgae biorefineries. Through comparative analysis and sustainability benchmarking, this study pinpoints bottlenecks in processing, supply chain limitations, and financial constraints that must be addressed to ensure long-term feasibility. Additionally, the integration of LCC highlights cost-effective strategies for reducing economic risks in commercial implementation.
3. Awareness and LCT. By applying LCT, this research promotes a sustainability-driven perspective on macroalgae utilization, emphasizing the importance of evaluating biorefinery systems beyond mere economic performance. The incorporation of S-LCA raises awareness about the socioeconomic implications of

macroalgae biorefineries, fostering discussions on equitable resource management, local employment opportunities, and industry-wide collaboration.

Thus, this Thesis bridges the gap between scientific advancements and industrial applications, offering a data-driven framework that can be directly integrated into macroalgae valorization strategies at regional, national, and European levels. The methodologies developed in this study are transferable to broader bioeconomy sectors, supporting policy development, investment strategies, and sustainable innovation in marine biotechnology. By addressing technical, economic, and social considerations, this Thesis provides a practical roadmap for guiding the transition toward sustainable macroalgae-based biorefineries, contributing to a circular bioeconomy and the broader goals of the EU Green Deal.

Research methodology

The structure of the applied research framework is illustrated in Fig. 1. The methodology integrates both qualitative and quantitative research techniques, including literature review, data collection and analysis, experimental data acquisition, case study definition, software modeling, and statistical analysis. The research follows a structured, stepwise approach to ensure a comprehensive and systematic evaluation of macroalgae biorefinery systems.

1. Step 1: Literature review and biorefinery system definition.

The first phase involves an extensive literature review to analyze the current landscape of macroalgae biorefinery systems, identifying key limitations and opportunities within the sector. This step aims to establish a comprehensive knowledge base for designing an optimal biorefinery system. Based on insights from literature and input from project partners within the TACO ALGAE project, a cascade biorefinery model for *F. lumbricalis* will be formulated. Additionally, alternative benchmark biorefinery designs will be outlined to enable comparative analysis.

2. Step 2: Data collection and environmental and economic assessment.

In this phase, a direct data collection strategy is implemented, incorporating primary data from the TACO ALGAE project's partners. In cases of data gaps, sectoral and literature data will be utilized to ensure completeness. Once the inventory analysis is established, covering key parameters such as material inputs, energy consumption, waste generation, and emissions, the LCA will be conducted. This analysis will initially focus on evaluating the environmental impact of different macroalgae harvesting and cultivation techniques, which are critical in determining the sustainability of biomass preparation operations. Subsequently, the environmental impact of various biorefinery designs proposed in Step 1 will be assessed.

Following the LCA, the LCC analysis will be conducted by assigning monetary values to inventory data, allowing for an economic comparison of the different biorefinery configurations.

3. Step 3: S-LCA development and analysis.

Since S-LCA methodologies are significantly underdeveloped for macroalgae systems, this step begins with the definition of a tailored S-LCA framework. Two levels of social analysis will be performed: i) value chain-level analysis, identifying social hotspots across the macroalgae production system; ii) community and company-level analysis, assessing the potential social impacts at a localized scale, focusing on small communities and businesses involved in macroalgae biorefining.

4. Step 4: LCSA and final sustainability index.

In the final phase, a comprehensive LCSA will be performed by integrating the results from Step 2 (LCA and LCC) and Step 3 (S-LCA). A multicriteria decision analysis (TOPSIS methodology) will be applied to calculate a final sustainability index, enabling a quantitative comparison of the proposed biorefinery designs. This approach will determine the most sustainable configuration for an *F. lumbricalis* biorefinery based on environmental, economic, and social sustainability indicators.

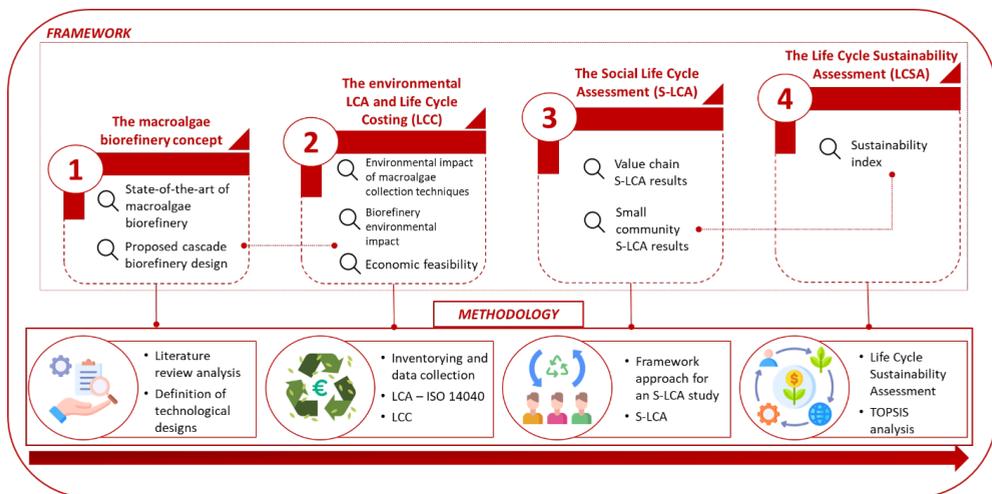


Fig. 1. The research methodology of the Doctoral Thesis.

Approbation of the research results

The results of the author's research have been presented and discussed in four scientific conferences and published in five peer-reviewed scientific journals.

1. N. Ferronato, **R. Paoli**, F. Romagnoli, G. Tettamanti, D. Bruno, and V. Torretta. Environmental Impact Scenarios of Organic Fraction Municipal Solid Waste Treatment with Black Soldier Fly Larvae based on a Life Cycle Assessment. *Environmental Science and Pollution Research* (2023), vol. 30, no. 1, pp. 1–19.
2. **R. Paoli**, B. Bjarnason, T. Ilmjärv, and F. Romagnoli. Off-Shore and On-Shore Macroalgae Cultivation and Wild Harvesting: an LCA-Based Evaluation from Baltic Sea Region Case Studies. *Environmental and Climate Technologies* (2023), vol. 27, no. 1, pp. 606–626.

3. F. Romagnoli, F. Spaccini, A. Boggia, **R. Paoli**, M. Feofilovs, B. Ievina, and L. Rocchi. Microalgae Cultivation in a Biogas Plant: Environmental and Economic Assessment through a Life Cycle Approach. *Biomass and Bioenergy* (2024), vol. 182, pp. 1–13.
4. F. Romagnoli, **R. Paoli**, A. Arias, E. Entrena-Barbero, T. Ilmjärv, K. Elvevold, and M. T. Moreira. *Furcellaria lumbricalis* macroalgae cascade biorefinery: a Life Cycle Assessment study in the Baltic Sea Region. *Journal of Cleaner Production* (2024), vol. 478, 143861.
5. A. Arias, E. Entrena-Barbero, T. Ilmjärv, **R. Paoli**, F. Romagnoli, G. Feijo, and M. T. Moreira. Conceptual design and environmental evaluation of the Biorefinery approach for R-phycoerythrin extraction and purification. *New Biotechnology* (2025), vol. 86, pp. 73–86.

Other scientific publications

1. F. Diaz, J. A. Vignati, B. Marchi, **R. Paoli**, S. Zanoni, and F. Romagnoli. Effects of Energy Efficiency Measures in the Beef Cold Chain: A Life Cycle-based Study. *Environmental and Climate Technologies* (2021), vol. 25(1), pp. 343–355.
2. F. Romagnoli, A. Arachchige, **R. Paoli**, M. Feofilovs, and B. Ievina. Growth Kinetic Model for Microalgae Cultivation in Open Raceway Ponds: A System Dynamics Tool. *Environmental and Climate Technologies* (2021), vol. 25(1), pp. 1317–1366.
3. **R. Paoli**, M. Feofilovs, A. Kamenders, and F. Romagnoli. Peat Production for Horticultural Use in the Latvian Context: Sustainability Assessment through LCA Modeling. *Journal of Cleaner Production* (2022), vol. 378.
4. A. Pettinaroli, S. Susani, R. Castellanza, E. Collina, M. Pierani, **R. Paoli**, and F. Romagnoli. A Sustainability-Based Approach for Geotechnical Infrastructure. *Environmental and Climate Technologies* (2023), vol. 27(1), pp. 738–752.
5. A. Pettinaroli, S. Susani, R. Castellanza, E. Collina, M. Pierani, **R. Paoli**, and F. Romagnoli. The Impact of a Permeation Grouting Technique Quantitatively Assessed Through a Process-Focused Life Cycle Assessment. *Environmental and Climate Technologies* (2023), vol. 27(1), pp. 797–812.
6. V. Mezzanotte, S. Venturelli, **R. Paoli**, E. Collina, and F. Romagnoli. Life Cycle Assessment of an industrial laundry: A case study in the Italian context. *Cleaner Environmental Systems* (2025), vol. 16, 100246.

Scientific publications submitted to a journal but not published yet

1. **R. Paoli** and F. Romagnoli (2025). A Review on Macroalgae Biorefineries: Technological Pathways and Life Cycle Assessment Perspectives. Submitted to *Environmental and Climate Technologies*.
2. **R. Paoli**, C. Foadelli, M. Traversi, G. Tomasoni, and F. Romagnoli (2025). Economic Feasibility of *Furcellaria lumbricalis* Biorefinery Designs: A Life Cycle Cost Approach. Submitted to *Sustainable Production and Consumption*.

3. **R. Paoli**, J. S. Pechsiri, A. Souza, and F. Romagnoli (2025). An Explorative Social Life Cycle Assessment for Wild Harvest and Cultivation of *F. lumbricalis* in the Baltic Sea Region. Submitted to Environmental and Climate Technologies.
4. **R. Paoli**, F. Romagnoli, M. Carnevale Miino, A. P. D. Baltrocchi, and V. Torretta (2025). Cascade Biorefinery of *Furcellaria lumbricalis* Macroalgae: Social Impact and Integration into a Life Cycle Sustainability Assessment. Submitted to Environmental and Climate Technologies.

Reports at scientific conferences

1. **R. Paoli**, B. Bjarnason, T. Ilmjärv, and F. Romagnoli. LCA-based comparison of different macroalgae cultivation and wild harvesting systems. International Scientific Conference of Environmental and Climate Technologies, CONECT 2023. Riga, Latvia, May 10–12, 2023.
2. **R. Paoli** and F. Romagnoli. An overview of the technological and environmental state-of-the-art of macroalgae biorefineries. International Conference of Algal Biomass, Biofuels and Bioproducts. Hawaii, USA, June 12–14, 2023.
3. F. Romagnoli, **R. Paoli**, A. Arias, E. Entrena-Barbero, T. Ilmjärv, K. Elvevold, and M. T. Moreira. *Furcellaria lumbricalis* macroalgae cascade biorefinery: a Life Cycle Assessment study in the Baltic Sea Region. International Conference of Algal Biomass, Biofuels and Bioproducts. Hawaii, USA, June 12–14, 2023.
4. **R. Paoli**, F. Romagnoli, A. Arias, T. Ilmjärv, K. Elvevold, and M. T. Moreira. Techno and social assessment of a macroalgae biorefinery in the Baltic Sea Region. WasteEng24 International Conference. Sendai, Japan, August 20–23, 2024.

Structure of the Doctoral Thesis

This Doctoral Thesis is written in English and consists of an introduction, three main chapters, conclusions and recommendations, references, and two annexes.

The Introduction presents the overall context and relevance of the research, outlines the objectives and methodology, and highlights the significance of the study's findings.

Chapter 1 provides a state-of-the-art review of the macroalgae biorefinery sector, identifying current opportunities and challenges. It also includes a literature review on the application of LCA to macroalgae systems, with a focus on sustainability aspects and end-use applications of macroalgae-derived products.

Chapter 2 introduces the technological design of the proposed *F. lumbricalis* cascade biorefinery, alongside two alternative system configurations: the single-product extraction and the three-line extraction designs. The chapter also details the methodological frameworks used to assess the environmental, economic, and social sustainability dimensions through the application of LCA, LCC, and S-LCA. It concludes with the application of the TOPSIS multi-criteria decision-making method to calculate a composite sustainability index within the LCSA framework.

Chapter 3 presents the results of the sustainability assessments (LCA, LCC, and S-LCA) across the different biorefinery designs and evaluates them through sensitivity analyses. It also

discusses the outcomes of the TOPSIS analysis, identifying the most sustainable design among the proposed scenarios.

The Conclusions and Recommendations chapter summarizes the key findings of the research and offers strategic guidance for future developments in the sector.

The full Doctoral Thesis comprises 185 pages, including 50 tables, 57 figures, 2 annexes, and 235 references.

1. STATE-OF-THE-ART ANALYSIS

To define the state-of-the-art in macroalgae-based biorefineries, a systematic literature review was carried out using the Scopus database. The review covered the period 2012–2024 and focused on both technological developments and the integration of LCA methodologies within macroalgal biorefinery systems. The methodology adhered to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) [19] guidelines to ensure transparency and reproducibility.

The research framework (illustrated in Fig. 1.1) followed two main investigative directions. The first addressed macroalgae biorefineries broadly, using a targeted search strategy that excluded LCA-related and microalgae studies. The second pathway focused specifically on studies linking LCA with macroalgae biorefineries, also filtering out research related to microalgae to maintain topical coherence.

The selection process was guided by predefined inclusion and exclusion criteria, documented in a PRISMA flowchart. The final dataset comprised studies that were systematically analyzed to extract insights into species classification (brown, green, and red macroalgae), extracted products, and applied biorefinery strategies. The evaluation also included an assessment of processing technologies in terms of their performance, limitations, and product yield.

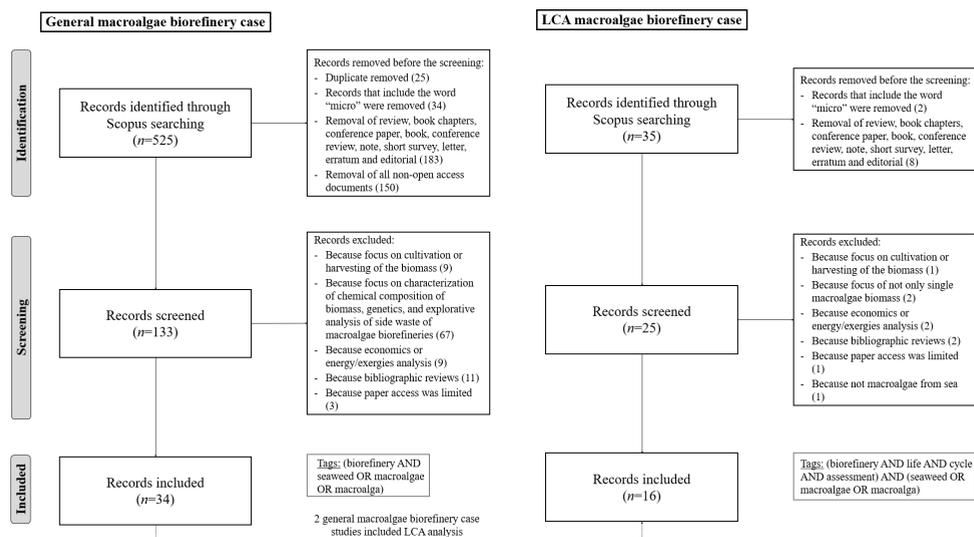


Fig. 1.1. Methodological framework. Flow of information through different phases of the systematic literature search. Diagram generated according to the PRISMA statement.

1.1. The macroalgae biorefinery system

The macroalgae biorefinery concept is built on the principle of transforming marine biomass into a wide array of marketable products, promoting circularity and sustainable resource use. It

aligns with the formal definition of a biorefinery as “the sustainable processing of biomass into a spectrum of marketable products and energy” [20]. Comparable to petroleum refineries that extract fuels and chemicals from crude oil, macroalgae biorefineries operate using renewable biological feedstocks such as seaweeds, agricultural waste, and aquaculture byproducts [21]. These systems involve upstream (cultivation and harvesting) and downstream (processing and valorization) stages, with a strong emphasis on site selection, process integration, and ecological compatibility. A well-designed macroalgae biorefinery is intended not only to optimize efficiency and yield but also to minimize environmental impacts while delivering socio-economic benefits [22].

Figure 1.2 provides a schematic overview of a macroalgae biorefinery.

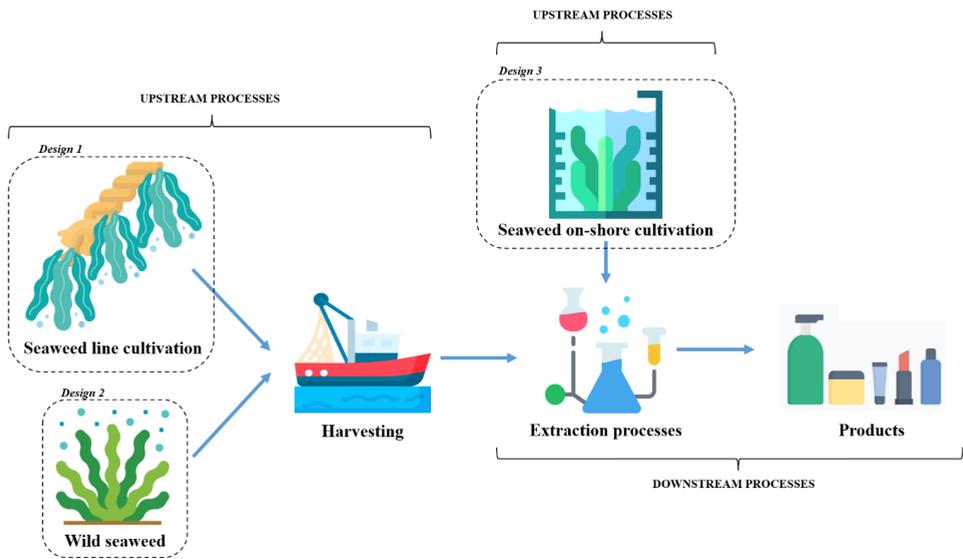


Fig. 1.2. Schematic representation of a hypothetical macroalgae biorefinery.

It illustrates key upstream operations, which include three primary biomass sourcing methods:

- i) Cultivation on artificial substrates (off-shore systems). Macroalgae are grown on ropes or net structures [23] placed in marine waters [24]. Species like *Laminaria digitata* and *Saccharina latissima* are commonly cultivated using this method [25].
- ii) Wild macroalgae harvesting. In regions like the North Atlantic [3], natural seaweed beds are harvested either manually or using mechanized vessels [26]. This practice must adhere to sustainability guidelines and seasonal limitations to preserve marine ecosystems [3], [27].
- iii) On-shore cultivation (land-based systems). Typically applied to green algae (e.g., *Ulva spp.*) [28], these systems operate in land-based tanks or raceways, offering better control over overgrowth conditions [29].

The downstream phase encompasses the transformation of macroalgal biomass into value-added products. The effectiveness of this phase depends on factors such as species composition,

extraction technology, environmental impact, economic feasibility, and scalability TRL [22]. To date, most valorization efforts have focused on single-product pathways like biomethane [30], bioethanol [31], and butanol [32] production. However, such linear models tend to overlook the full resource potential of macroalgae, often resulting in economic inefficiencies and environmental drawbacks.

In response, the cascade biorefinery model has emerged as a superior alternative [33]. This integrated strategy involves sequential extraction of macromolecules, diversification of end-products across sectors, enhanced resource utilization, and minimized waste. This multi-product extraction model represents a shift toward a circular and sustainable biorefinery system [34]. By maximizing the value derived from each unit of biomass, cascade biorefineries offer greater profitability and resilience, positioning macroalgae as a key component in the transition to a bio-based economy.

Macroalgae offer a wide array of bioactive compounds and functional components, with growing relevance across sectors such as food, agriculture, pharmaceuticals, animal feed, and energy. Some examples are reported below.

- Food industry

The use of macroalgae in the food sector is driven by their nutritional value, culinary versatility, and increasing consumer demand for sustainable, plant-based options [35]. Macroalgae are consumed fresh, fermented, or as powdered supplements [36]. They are incorporated into a variety of products, including snacks (e.g., seaweed-based crackers), beverages (e.g., beers and soft drinks), and functional food blends [6]. Their integration into cereal-based products further enhances nutritional profiles, making macroalgae a valuable component in health-conscious diets [37].

- Agriculture and horticulture

Macroalgae have a longstanding role as natural fertilizers due to their rich mineral content and fibrous structure, which improves soil quality and moisture retention. Fertilizer applications include solid forms (powdered or granulated) [38] and liquid extracts, such as sap obtained through mechanical pressing [6]. These formulations are rich in micronutrients, vitamins, and plant growth regulators, contributing to crop productivity and stress resilience [39]. In addition to fertilizing properties, macroalgae-based inputs have demonstrated biofungicidal activity [40]. Integrating macroalgal residues from biorefineries into agricultural use presents a sustainable model for resource circularity. However, monitoring for metal accumulation and chemical stability over time remains essential for safe application [41].

- Animal feed

Macroalgae are increasingly used as feed supplements due to their high content of vitamins, fibers, and minerals [42]. *Ulva* species, in particular, have been associated with improved poultry health, egg quality [43], and antimicrobial benefits, including action against the Newcastle disease virus [44]. Brown macroalgae have shown the potential to improve weight gain and reduce mortality in poultry [45], while red macroalgae have been linked to enhanced egg production in quails. [46]. In cattle, supplementation with *Undaria pinnatifida* improved calf health and birth weights. [47]. Combinations of brown algae (e.g., kelp, *Fucus*) have been found to increase digestibility and nutrient uptake in ruminants [6]. In swine, alginate

oligosaccharides derived from brown macroalgae show antibacterial [48] and prebiotic effects, supporting gut health and immunity [49].

- Bioactive compounds

To survive in dynamic marine environments, macroalgae have evolved to produce diverse bioactive molecules. These compounds are increasingly valued in pharmaceutical, nutraceutical, and cosmetic industries due to their antioxidant, antimicrobial, anti-inflammatory, and antiviral properties [50]. Table 1.1 categorizes key bioactives according to macroalgae type, biofunctional properties, and industrial relevance.

Table 1.1

List of some of the macroalgae bioactive compounds

Types of macroalgae	Bioactive compounds	Bioactive effects	References
<i>Laminaria</i> (brown)	Sulfate ester	Tumor-inhibiting and anticoagulant agent	[51]
	Laminarin	Antibacterial and a boost for the immune system	[6]
<i>M. nitidum</i> (green), <i>L. pinnatifida</i> (brown) <i>P. yezoensis</i> (red)	Polysaccharides	Antihypertensive and antihyperlipidemic effects	[52]
<i>Ulva spp.</i> (green) <i>H banksia</i> (brown)	Fatty acids	Anti-inflammatory action	[53]
Brown macroalgae (general)	Polyphenols	Antioxidant and anti-inflammatory effects	[54]
	Phloroglucinol, fucoxanthin, and fucoidan	Antitumoral for breast cancer	[55]
Red macroalgae (general)	Polyphenols	Protection against cardiovascular diseases and diabetes	[56]
		Phycobiliproteins	Natural colorant for food and cosmetics
		Antimicrobial, antioxidant, anti-inflammatory, and neuroprotective action	[58]
<i>Ulva spp.</i>	Acidic	Used in cosmetic formulation	[59]
<i>E. cottonii</i> (red)	Phlorotannins	Natural tyrosinase inhibitor for skin whitening	[60]
<i>E. cava</i> (brown)	Phlorotannins	Healing skin inflammation	[61]

- Biofuels and bioenergy

Macroalgae serve as a promising biomass source for renewable energy production. Their suitability for biofuel applications arises from favorable traits such as low lignin content, a balanced C/N ratio, and diverse chemical composition. Conversion pathways include anaerobic digestion, fermentation, gasification, pyrolysis, and hydroprocessing [62]. Biogas production is currently one of the most feasible macroalgae-based energy applications due to the ease of integration into existing systems [63]. In contrast, bioethanol and biobutanol production face challenges related to high moisture content, which impairs processing efficiency [64]. Thermochemical conversion technologies also struggle with the presence of ash, metals, and low lipid content in macroalgae, limiting their viability for biodiesel and bio-oil production [65]. Significant technical and economic barriers, particularly in large-scale cultivation, dewatering, and logistics, still hinder widespread adoption of macroalgae for bioenergy [63].

1.2. Take-home messages

Limitations of the macroalgae biorefinery systems

The systematic literature review identified several critical challenges hindering the development and large-scale deployment of macroalgae biorefineries. These gaps underline the need for further research, such as the work undertaken in this Doctoral Thesis, to address both technological and environmental bottlenecks and guide the evolution of sustainable macroalgal value chains. Three main challenges have been identified as priorities for future research and innovation in macroalgae biorefinery systems:

- Technological maturity

Many macroalgae biorefinery initiatives remain in the early research or pilot phases, lacking technological readiness for full industrial deployment. The extraction of high-value compounds, such as peptides and polysaccharides, requires tailored, species-specific methods that often lack scalability. Moreover, current conversion technologies frequently suffer from inefficiencies in energy consumption and yield optimization. A major barrier to progress lies in the disconnection between technological development and environmental evaluation. While research has focused on enhancing process efficiency, LCA studies have not kept pace, resulting in a lag between innovation and sustainability assessment. This misalignment prevents the timely identification of environmental trade-offs, limiting the integration of sustainability metrics into biorefinery design and optimization strategies.

- Biomass availability and quality

Macroalgae biomass is inherently variable due to environmental dependencies. Factors such as water temperature, light, and nutrient availability fluctuate seasonally and regionally, affecting both biomass yield and biochemical composition. These variations have significant implications for process design and consistency, particularly for applications such as biodiesel production where lipid content is a key parameter. Addressing these challenges requires the development of adaptive processing systems and robust feedstock management strategies. Ensuring year-round biomass availability with consistent quality is essential to the economic and operational viability of macroalgae-based biorefineries.

- Environmental impacts and sustainability gaps

While macroalgae cultivation is often promoted as an environmentally friendly alternative due to its low land use and potential for carbon capture, large-scale implementation may carry ecological risks. These include the potential spread of invasive species, habitat disruption, nutrient imbalance in marine ecosystems, and the risk of eutrophication due to nutrient runoff. To validate the environmental benefits of macroalgae biorefineries, a comprehensive LCA must be applied across the entire value chain. It is essential to avoid burden shifting, where benefits in greenhouse gas mitigation come at the cost of other environmental impacts. However, the current distribution of LCA studies is skewed heavily toward brown macroalgae, with negligible coverage of green and red species. This imbalance severely limits the capacity for integrated sustainability assessment and emphasizes the urgency of expanding LCA research to include all macroalgae groups.

Needs and opportunities for macroalgae biorefinery systems

Based on the findings of the literature review, this Thesis outlines several strategic recommendations aimed at advancing the development of macroalgae biorefineries. These proposals address current limitations in technology, sustainability, and policy, while also highlighting future research (i.e., like this work) and innovation pathways essential for fostering a resilient and circular bioeconomy.

- **Integrated biorefinery approaches**

Maximizing biomass valorization through integrated processing strategies is essential to overcoming economic barriers in macroalgae-based industries. The implementation of circular models, where residual biomass from primary processes (e.g., biofuel production) is repurposed for secondary uses such as biogas generation or agricultural applications, enhances resource efficiency while minimizing waste. This cascading approach not only increases economic returns but also contributes to broader environmental sustainability objectives.

- **Standardization in cultivation and harvesting techniques**

Despite significant progress in biomass conversion technologies, standardized methods for macroalgae cultivation and harvesting remain underdeveloped. Seasonal variability in biomass quality poses a challenge to biorefinery stability and output consistency. Controlled-environment systems, including land-based aquaculture, offer a viable solution by improving predictability in yield and quality. In parallel, innovation in sustainable harvesting practices is necessary to ensure minimal ecosystem disruption. Precision aquaculture tools, selective harvesting strategies, and automation can significantly improve both biomass supply chain efficiency and environmental performance.

- **LCA as a design tool**

The role of LCA must evolve from retrospective analysis to a proactive process design and optimization tool. By identifying environmental hotspots, LCA can guide improvements in energy use, emissions, and resource inputs. Region-specific LCA adaptations are particularly important, allowing for site-sensitive modeling of cultivation systems, processing techniques, and transport logistics. Further, more rigorous environmental quantification of green technologies is required. This includes evaluating energy-efficient processes, eco-friendly extraction methods, and circular economy principles, ensuring that claimed sustainability benefits are supported by empirical evidence.

- **Technological innovation and scalability**

Achieving industrial-scale implementation requires the application of emerging technologies to enhance operational efficiency. Genetic engineering and selective breeding can support the development of macroalgal strains with superior yields, resilience, and biochemical profiles. Additionally, the integration of automation, artificial intelligence, and real-time bioprocess monitoring enables optimization of biomass production and conversion processes. Data-driven precision aquaculture systems can reduce operational costs, improve productivity, and enable scalable, adaptive responses to environmental variability.

- **Policy and regulatory support**

The advancement of macroalgae biorefineries depends on supportive policy frameworks that reduce financial risk and stimulate investment. Incentives such as subsidies, tax credits,

and research funding are vital to fostering innovation and commercial deployment. Regulatory alignment with climate mitigation goals, such as emissions reductions and renewable energy targets, can also create favorable market conditions for macroalgae-derived products. Moreover, marine spatial planning and aquaculture legislation must ensure the responsible use of ocean resources, balancing ecological integrity with industrial development.

- Market development for macroalgae-based products

Expanding demand for macroalgae-derived products is central to ensuring the economic viability of biorefineries. Sectors such as bioplastics, pharmaceuticals, cosmetics, and nutraceuticals present significant growth opportunities. However, barriers remain in terms of cost competitiveness, regulatory approval, and consumer awareness. To address these challenges, efforts should focus on public awareness campaigns, industry-research partnerships, and sustainability certification schemes. Eco-labeling initiatives can further promote transparency and build trust in macroalgae-based alternatives.

- Integration with S-LCA

Social sustainability must be embedded within macroalgae biorefinery development. Coastal communities, often central to macroalgae harvesting and processing, stand to benefit significantly from job creation, improved food security, and economic diversification. The inclusion of S-LCA can support the evaluation of employment and skills development in rural and coastal regions, impacts on traditional livelihoods and small-scale fisheries, ethical sourcing and fair trade practices, community engagement, and stakeholder participation. To ensure equitable distribution of benefits, participatory governance models, community co-management structures, and transparent knowledge-sharing platforms should be implemented. These mechanisms can enhance local ownership, mitigate conflict, and ensure the inclusive development of macroalgae-based value chains.

2. METHODOLOGY

2.1. The technological designs for the *F. lumbricalis* biorefinery

The *F. lumbricalis* macroalgae

F. lumbricalis (Fig. 2.1) is a red macroalga (*Rhodophyta*) [66] predominantly distributed in the North Atlantic and Arctic Ocean, with notable abundance in the Baltic Sea region [67]. It is recognized as one of the most ecologically dominant red algae species in this area, particularly within the Estonian marine environment. This species exhibits versatile habitat adaptability, typically growing on hard substrates such as rocks and stones. However, it also colonizes softer seabeds, including sandy and muddy bottoms, where it forms dense, monotypic underwater meadows [66]. As a perennial organism, *F. lumbricalis* has a natural lifespan of 5 to 10 years and can thrive at depths reaching 30 meters. Its optimal growth, however, is generally observed between 8 and 12 m [68]. Notably, it demonstrates high tolerance to low-salinity environments, a trait that allows it to flourish under the unique conditions of the Baltic Sea. [66].

The collection site for the biomass investigated in this Thesis is located in Kassari Bay, Estonia (58.805°N, 22.786°E), at a depth of seven meters. This region contains an estimated stock of approximately 140,000 tons of *F. lumbricalis*, most of which remains unexploited. This represents a considerable opportunity for sustainable biorefinery development.



Fig. 2.1. The *F. lumbricalis* macroalgae [69].

The macro elemental composition of *F. lumbricalis* reveals its potential for multiple valorization pathways: carbohydrates (39.82 %), lipids (30 %), proteins (28.32 %), and ash content (1.86 %). For clarity and consistency in interpreting inventory data and functional unit calculations throughout this work, it is important to note the following conversion factor: 1 ton of dry weight (DW) *F. lumbricalis* is equivalent to 7.6 tons of fresh weight (FW). This ratio is applied in all relevant assessments to ensure accurate mass balance and comparative analysis across process stages.

The upstream processes (macroalgae collection)

In alignment with current industrial practice, wild harvesting (WH) has been selected as the preferred method for sourcing *F. lumbricalis*. While one experimental study has investigated artificial cultivation, this method remains at an early stage of development and has not yet

advanced toward commercialization [70]. The WH approach reflects the operational model adopted by the industrial partner Vetik OÜ [69], a key collaborator within the TACO ALGAE project. The company holds annual harvesting licenses for *F. lumbricalis*, permitting the extraction of up to 1,000 tons per license. The WH scenario examined focuses on biomass collection in Kassari Bay, Estonia. The operational process is illustrated in Fig. 2.2 and comprises several distinct phases, particularly described in the full Thesis manuscript. The operational setup not only reflects real-world industry practice but also establishes a baseline for evaluating the environmental and economic performance of the WH approach within macroalgae biorefinery frameworks.

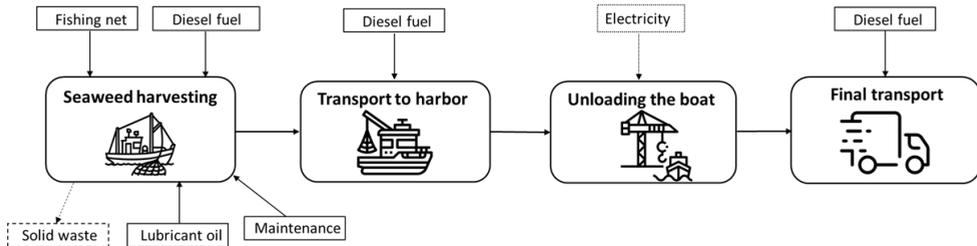


Fig. 2.2. Flowchart for the WH process. From approbation publication No. 2 [71].

The proposed cascade biorefinery design (downstream processes)

To enable the full valorization of *F. lumbricalis*, a multiproduct cascading biorefinery concept has been developed in collaboration with Vetik OÜ and Nofima AS, both partners in the TACO ALGAE project. The proposed biorefinery system allows for the sequential recovery of high-value products (i.e., pigments, proteins, and carrageenan) while the remaining biomass is repurposed either as a biostimulant for agriculture or as feedstock for biogas production. This integrated design ensures that all fractions of the macroalgal biomass contribute to value-added outputs. A schematic representation of the biorefinery process is provided in Fig. 2.3.

The biorefinery process begins with pre-treatment through biomass washing, a critical step to ensure purity before downstream processing. This stage removes sand, marine organisms, and other debris, requiring approximately 10 cubic meters of water per ton of fresh seaweed to meet quality standards.

Pigment extraction is prioritized as the first valorization line, given the high commercial value of these compounds. The process uses a 1:1 water-to-biomass ratio, with separation achieved through centrifugation using Flottweg Z3E and Alfa Laval AFPX 810 units. Microfiltration and ultrafiltration are subsequently applied to purify the pigment extract, enhancing product quality. The remaining biomass is forwarded to the next extraction stage.

In the second phase, protein extraction is carried out using enzymatic hydrolysis. The biomass is heated to 40 °C, then mixed with water, alcalase enzyme, and potassium hydroxide under constant stirring for two hours. Following hydrolysis, the protein-rich solution is separated and purified through microfiltration, while the remaining solids proceed to carrageenan extraction.

Carrageenan recovery involves thermal processing of the residual biomass at 95 °C with the addition of water and potassium hydroxide. The process is followed by phase separation using a tricanter system, and final product concentration is achieved using Alfa Laval AlfaVap1 technology with thermal vapor recompression.

The residual biomass, now considered waste from the carrageenan extraction stage, becomes the input for two possible downstream applications. In the first option, the residual biomass is repurposed as a fertilizer additive due to its biostimulant properties. Its mineral-rich composition supports plant growth, soil health, and crop resilience, as further discussed in Section 1.1. As an alternative valorization route, the biomass residue can be directed to biogas production. Based on the framework outlined by Fasahati et al. (2022) [72], this pathway involves anaerobic digestion of organic residues to produce biogas, followed by energy recovery through a boiler and turbogenerator system.

The proposed cascading biorefinery model is theoretically designed to yield 20 kg of pigments, 100 kg of proteins, and 200 kg of carrageenan from 1,000 kg of dry *F. lumbricalis*. However, it is important to note that these values are derived from process simulations and laboratory analyses and have not yet been validated at an industrial scale.

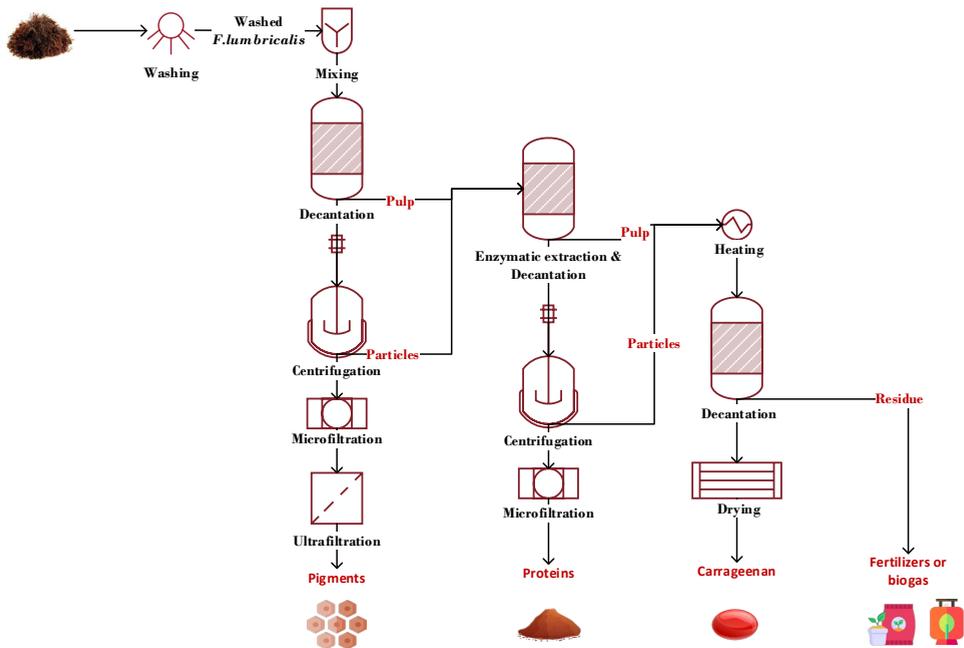


Fig. 2.3. System diagram for the cascade biorefinery design. Adapted from the approbation publication No. 4 [73].

It is important to recognize that the biorefinery configuration proposed in this Thesis represents only one of several potential design pathways. During the conceptual phase, alternative techniques for pigment extraction, such as ultrasound-assisted (UAE) and enzymatic

(EAE) methods, were also evaluated for their potential to enhance energy efficiency and process performance [74]. However, the water-based extraction method was ultimately selected, primarily due to the availability of reliable and consistent primary data, which enables a more accurate and robust sustainability assessment. Nevertheless, the potential environmental and economic benefits of these alternative extraction techniques are further examined and critically discussed in the results chapter.

The alternative biorefinery designs (downstream processes)

The alternative biorefinery designs developed in this research represent two conventional approaches that have been previously documented in the literature, contrasting with the CB model described earlier. Up to the pre-treatment, all designs follow identical technological layouts, meaning that *F. lumbricalis* is harvested and pre-treated using the same procedures in all three cases. However, a major divergence occurs in the biorefinery extraction stages, specifically in how biomass is processed, how waste is managed, and the conceptualization of final products. The two designs are:

1. Single-product extraction

The single-product extraction represents the most direct scenario in biorefinery operations. It is widely applied in LCA studies in the literature, particularly concerning the use of macroalgae for energy production, like bioethanol and biogas [75]. These studies are valuable for understanding the phenomenon and identifying the benefits of various extraction technologies, helping to determine the critical parameters and optimal processes for maximizing product yield. However, this approach does not align with the circularity concept, as it does not involve the systematic reuse of extraction residues. As a result, the biomass is utilized for a single product extraction, leaving other valuable compounds in the residues. Consequently, more initial biomass is required to obtain equivalent quantities of valuable compounds compared to a cascade approach. The system modeled in this study includes separate lines for pigment, protein, and carrageenan extractions. For comparability, it is assumed that seaweed waste continues to be used to produce an equivalent amount of fertilizers or biogas. Figure 2.4 shows the technological scheme for the single-product extraction design.

2. Three-line extraction

The three-line extraction configuration offers an alternative to the cascading biorefinery by distributing the initial biomass evenly across three separate processing lines dedicated to pigment, protein, and carrageenan extraction, as illustrated in Fig. 2.5. While the feedstock input remains identical to the cascade model, this approach results in significantly lower product recovery efficiency, thereby reducing the overall effectiveness of *F. lumbricalis* valorization. A primary drawback of this model lies in the underutilization of valuable bioactive compounds. Each extraction line processes only one-third of the total biomass input, and residual fractions containing usable compounds are not further exploited. Instead, these residues are directed toward secondary applications such as biogas generation or fertilizer use, bypassing the opportunity for full biorefinery integration. In this scenario, one ton of *F. lumbricalis* biomass is divided equally (i.e., 333.33 kg per extraction line). As a result, final product yields are

reduced when compared to the cascade approach: only 13.33 kg of pigment, 33.33 kg of protein, and 66.67 kg of carrageenan are recovered.

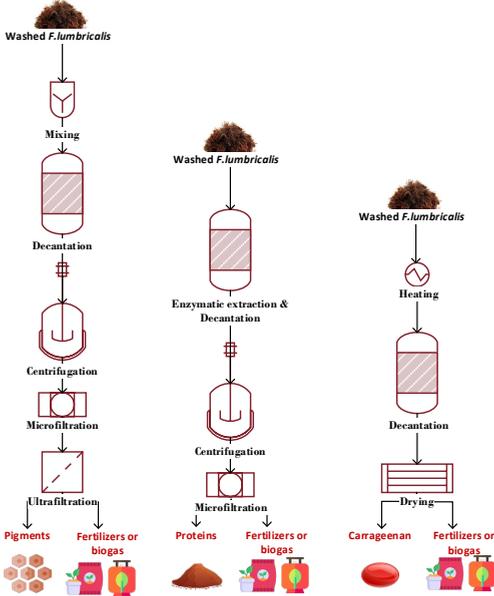


Fig. 2.4. System diagram for the single-product extraction design. From the approbation publication No. 4 [73].

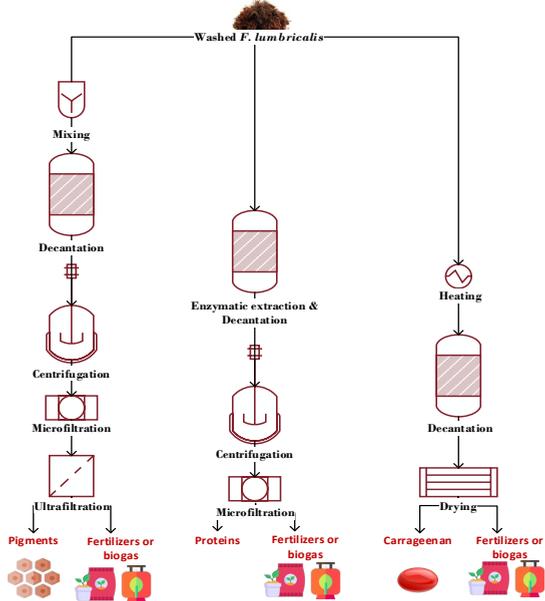


Fig. 2.5. System diagram for the three-line extraction design. From the approbation publication No. 4 [73].

2.2. The Environmental life cycle assessment

LCA is a standardized methodology used to evaluate the potential environmental impacts of a product, process, or service across its entire life cycle, from raw material extraction through production, transportation, use, and end-of-life disposal. Following the ISO 14040 and ISO 14044 standards, LCA is structured into four main phases: goal and scope definition, inventory analysis, impact assessment, and interpretation [76].

The first phase, goal and scope definition, sets the foundation for the study by establishing the system boundaries, intended applications, and the level of detail required. The functional unit (FU) is introduced here as a reference point, playing a vital role in quantifying system functions and ensuring comparability across different assessments. The system boundary delineates which unit processes are included in the analysis and ensures that all relevant inputs and outputs are captured as elementary flows.

The life cycle inventory (LCI) analysis phase involves gathering data and conducting the necessary computations to quantify the system's resource use and emissions. This is an iterative process, with data refinement enhancing the model's accuracy. Inputs and outputs are typically grouped into categories such as resource and energy inputs, product and co-product outputs, emissions to air, discharges to water, and waste to land.

The third phase, life cycle impact assessment (LCIA), evaluates the significance of the inventory results by translating resource flows and emissions into potential environmental impacts. This step provides a clearer picture of the environmental burdens associated with the system under study. Multiple LCIA methodologies are available, each offering different perspectives and impact categories for assessing environmental performance.

The interpretation phase consolidates and synthesizes all findings, ensuring coherence with the study's initial goals and scope. This phase facilitates a comprehensive discussion of the system's environmental implications and supports decision-making by identifying key drivers, trade-offs, and improvement opportunities.

To validate and contextualize the LCA methodology adopted in this Thesis, it was initially applied to systems exhibiting comparable characteristics to the proposed *F. lumbricalis* cascade biorefinery. The first reference case involved the assessment of a microalgae cultivation system [77], which provided critical insights into parameter selection, particularly regarding energy consumption, waste and wastewater management, and biogas valorization. Key findings from this study, especially those related to the combined heat and power (CHP) unit, were adapted for the *F. lumbricalis* model. Additionally, the geographic proximity within the Baltic region allowed for the transfer of relevant regional modeling parameters, particularly those concerning energy infrastructure and medium-scale biogas system dynamics.

A second reference case focused on the LCA of an innovative food waste treatment system utilizing Black Soldier Fly larvae [78]. This system was selected for its closed-loop operational model, which closely aligns with the circular resource recovery principles underlying the cascade biorefinery. Specifically, it provided valuable methodological guidance on inventory modeling in biomass-based systems and on the development of alternative scenarios. These

methodological elements were subsequently refined and tailored to the specific requirements of the *F. lumbricalis* biorefinery assessment.

LCA for different techniques of harvesting and cultivation for the upstream stage

The primary objective of this initial LCA is to identify environmental hotspots associated with the WH of *F. lumbricalis* in Kassari Bay, Estonia. As the dominant and currently sole commercial method for collecting this species, WH serves as the baseline scenario for environmental performance evaluation. To contextualize and benchmark the environmental implications of WH, two alternative macroalgae cultivation techniques were assessed for comparative purposes. Given the absence of documented large-scale cultivation practices for *F. lumbricalis*, analogous systems involving other macroalgae species were adopted. The off-shore cultivation (OFC) scenario was modeled based on the detailed process inventory developed by Seghetta et al. (2016) [24], which outlines the cultivation of brown macroalgae in open marine environments. For the on-shore cultivation (ONC) scenario, data were sourced from the HYNDLA [79], another TACO algae partner, which tested land-based cultivation of the red macroalga *Schizymenia valentinae*.

The FU was defined as “1 ton of fresh macroalgae harvested or produced, assuming 100 % species purity.” This unit ensures methodological consistency and facilitates comparability with existing LCA literature on macroalgae systems. The LCA was performed using SimaPro 9.4 software, developed by Pré Consultants [80]. The LCA in this Thesis relied on the Ecoinvent 3.8 database, chosen for its comprehensive, peer-reviewed datasets and wide recognition in the field. Covering diverse sectors and regions, Ecoinvent ensures data consistency and supports both attributional and consequential models. Its compliance with ISO 14040/44 standards guarantees methodological transparency, reproducibility, and scientific rigor [81].

- System boundaries

For the WH, the system described in Section 2.1 was adopted.

The scenario of the ONC is summarized in Fig. 2.6; the detailed description is reported in the full Thesis manuscript. The ONC system modeled in this research is based on primary data obtained from the HYNDLA, which focuses on the cultivation of the red macroalga *Schizymenia valentinae* in Iceland. Although this species differs from *F. lumbricalis*, the system provides a relevant analog for evaluating the environmental implications of land-based red macroalgae cultivation.

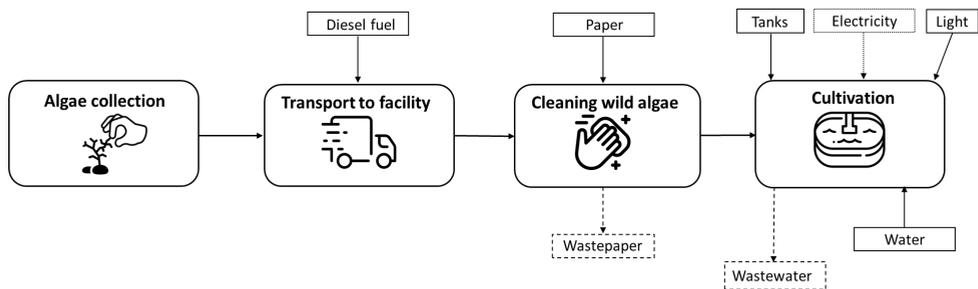


Fig. 2.6. Flowchart for the ONC process. From approbation publication No. 2 [71].

The schematic definition of the system boundaries for the OFC is detailed in Fig. 2.7 and described in the full Thesis manuscript. The OFC system evaluated in this study is based on the model developed by Seghetta et al. (2016) [24] for *L. digitata*, selected due to its geographical and environmental relevance to the Baltic Sea Region, specifically Denmark. Although the system is not explicitly designed for *F. lumbricalis* or *S. valentinae*, it offers a robust and transferable process inventory and shares functional similarities with OFC designs used for red macroalgae in other studies [82], [83].

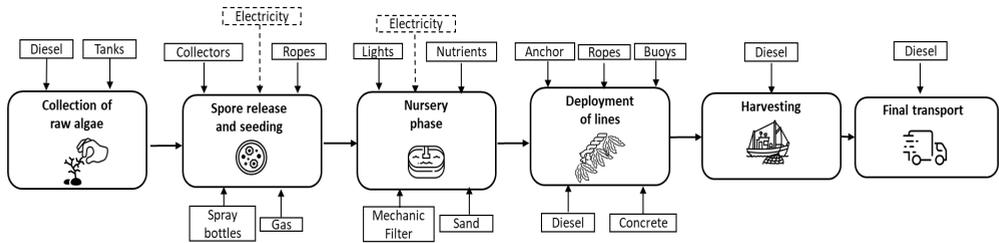


Fig. 2.7. Flowchart for the OFC process. From approbation publication No. 2 [71].

- Alternative scenarios

To explore potential improvements in system sustainability, this study introduces a series of alternative scenarios (AS) that modify selected parameters from the baseline configuration. These scenarios are designed to assess how targeted changes can reduce environmental impacts across the macroalgae sourcing systems. The analysis of alternative scenarios provides insight into how system performance can evolve through technological upgrades, process optimization, and the adoption of more sustainable practices. Each scenario addresses a specific operational factor identified as environmentally significant in the initial LCA. The proposed alternative scenarios include:

1. AS1 – implementing solar energy to supply 50 % of the electricity demand in both ONC and OFC systems. This adjustment is motivated by the observation that electricity consumption in these systems plays a crucial role in determining environmental impact.
2. AS2 – modifying the ONC system by replacing artificial LED lighting with natural sunlight to reduce energy consumption and improve sustainability.
3. AS3 – introducing an environmentally friendly antifouling agent, replacing the copper oxide-based solution currently used in the WH scenario. The new antifouling agent is modeled from the publication of Lin and Usino (2014) [84].
4. AS4 – reducing diesel consumption by 10 % in both the WH and OFC scenarios, focusing on vessel fuel efficiency improvements to lower emissions and resource use.

- LCIA selection

To evaluate the environmental performance of the three macroalgae sourcing scenarios, the Environmental Footprint 3.0 impact assessment method [85] was chosen. A carefully selected set of impact indicators was applied to ensure the relevance and completeness of the assessment,

reflecting the particularities of macroalgae harvesting and cultivation systems. These indicators are presented as follows: climate change (CC), particulate matter (PM), acidification potential (AP), eutrophication freshwater (EF), eutrophication marine (EM), ecotoxicity freshwater (ECF), land use (LU), water use (WU), resource use fossil (RF) and resource use minerals and metals (RM&M). The rationale behind the selection of these indicators, along with their detailed descriptions, is provided in the full Thesis manuscript.

- LCI

The LCI dataset for the WH scenario is presented in Table 2.1. All values have been normalized to the FU and adjusted based on the operational lifetime of equipment and processes, where applicable. The dataset reflects real-world conditions and operational practices by scaling the inventory according to the total quantity of *F. lumbricalis* harvested by Vetik OÜ in 2021.

Table 2.1

LCI for the WH scenario. Adapted from approbation publication No. 2 [71]

	Category	Material/ component	Input on SimaPro software	Quantity	Unit	Data source
Seaweed harvesting						
<i>Inputs</i>	Raw materials	Fishing net	Nylon 6-6 {RER} market for nylon 6-6 APOS, U	1.67	kg	Primary data
		Diesel for harvesting	Diesel, burned in fishing vessel {EU} diesel, burned in fishing vessel APOS, U	190	MJ	Primary data
		Lubricant oil	Lubricating oil {RER} market for lubricating oil APOS, U	2.75	kg	Primary data
		Epoxy paint	Epoxy resin, liquid {RER} production APOS, U	1.25	kg	Primary data
		Antifouling agent	Specific model from [84]	0.42	kg	Primary data
		Steel for the boat	Long liner, steel {RER} long liner construction, steel APOS, U	4.00	kg	[86]
<i>Outputs</i>	Raw materials, waste	Sand, clay, and mud waste	Refinery sludge {Europe without Switzerland} treatment of refinery sludge, sanitary landfill APOS, U	21	kg	Primary data
Transport to the harbor						
<i>Inputs</i>	Raw materials	Diesel for transport	Diesel, burned in fishing vessel {EU} diesel, burned in fishing vessel APOS, U	52.77	MJ	Primary data
Unloading the boat						
<i>Inputs</i>	Energy	Electricity for unloading the boat	Electricity, medium voltage {EE} market for APOS, U	0.69	kWh	Primary data
Final transport						
<i>Inputs</i>	Transport	Freight lorry	Transport, freight lorry 7.5-16 metric ton, euro5 {RER} market for transport, freight, lorry 7.5-16 metric ton, EURO5 APOS, U	53.20	tkm	Primary data

The inventory data for the ONC scenario are detailed in Table 2.2. As with the WH scenario, all values have been normalized to the FU and adjusted according to the expected lifetime of equipment and operational processes, where relevant. The dataset is derived from the total biomass of red macroalgae cultivated by HYNDLA in 2021, ensuring direct correlation with

actual production data. Due to the shared infrastructure used for water pumping, serving both the cultivation tanks and other facility functions, it was not feasible to isolate macroalgae-specific energy consumption. To address this limitation, electricity use for seawater pumping was estimated using the equation proposed by Piccino et al. (2016) [87], providing a standardized and robust approach to modeling this parameter within the system boundary.

Table 2.2

LCI for the ONC scenario. Adapted from approbation publication No. 2 [71]

	Category	Material/ component	Input on SimaPro software	Quantity	Unit	Data source
Transport to the facility						
<i>Inputs</i>	Transport	Passenger car	Transport, passenger car, EURO 4 {RER} market for APOS, U	15	km	Primary data
Cleaning the wild algae						
<i>Inputs</i>	Raw materials	Paper tissues	Tissue paper {GLO} market for APOS, U	0.34	kg	Primary data
<i>Outputs</i>	Waste	Paper waste	Waste paper, unsorted {Europe without Switzerland} market for APOS, U	0.34	kg	Primary data
Cultivation						
<i>Inputs</i>	Raw materials	Tanks	Polystyrene, general purpose {GLO} market for APOS, U	1.40	kg	Primary data
		Sea water	Water, Saline water consumption	32,640	kg	Primary data
		Water cleaning	Tap water {Europe without Switzerland} market for APOS, U	1,120	kg	Primary data
		Soap cleaning	Modeled based on technical datasheet	0.446	l	Primary data
		LED lights	Light emitting diode {GLO} market for APOS, U	0.1587	kg	Primary data
		Water pump	Cast iron {GLO} market for APOS, U	12	kg	Primary data
	Energy	Electricity for lights	Electricity, medium voltage {IS} market for APOS, U	4,652	kWh	Primary data
		Electricity for pumps	Electricity, medium voltage {IS} market for APOS, U	2.22	kWh	Primary data
	Land use	Cultivation facility	Occupation, industrial area	333	m ² a	Primary data
	<i>Outputs</i>	Wastewater	Wastewater	Wastewater, from residence {CH} market for wastewater, from residence APOS, U	1.12	m ³

The use of “electricity, medium voltage” in the modeling reflects the intention to simulate conditions representative of a potential industrial-scale operation.

For the OFC scenario, the LCI is based on secondary data sourced from the literature. As such, the complete inventory is reported in the full Doctoral Thesis manuscript. To ensure methodological consistency and comparability with the WH and ONC scenarios, all values have been scaled in accordance with the defined FU. Similarly, detailed inventories and modeling

assumptions for the alternative scenarios (AS1–AS4) are presented in full in the main Thesis document.

LCA on the full biorefinery system

The core objective of this LCA is to evaluate the environmental performance of the proposed CB system for *F. lumbricalis*, as described in detail in Section 2.1. In addition, the study provides a comparative analysis between the innovative cascade model and two alternative biorefinery configurations: a single-product extraction (SPE) model and a three-line extraction (TLE) system. To ensure a comprehensive and multidimensional assessment, two FUs were defined. The first, FU1, is based on a biomass-oriented perspective and is set at 1 ton of DW *F. lumbricalis* treated. This unit supports a process-level evaluation of environmental impacts, enabling the identification of critical stages and emission hotspots within the biorefinery system.

FU2 is product-oriented and corresponds to the cumulative output of the three high-value compounds targeted in the cascade system: 20 kg of pigments, 100 kg of proteins, and 200 kg of carrageenan. This unit facilitates a comparative evaluation of system efficiency and resource utilization across the CB, SPE, and TLE configurations. Notably, the significantly lower output yields in the TLE scenario require functional compensation to match the performance of the CB. To address this shortfall, commercially available substitutes were introduced to ensure functional equivalence. Specifically, disodium disulphite was selected as a proxy for the pigment fraction, replicating the functional properties of Allura Red AC [88], [89]; soybean-based protein feed was used to offset the protein deficit, and potato starch served as a thickening agent to substitute for carrageenan [90]. The adoption of dual functional units is consistent with best practices in the LCA of biorefinery systems [91], [92]. This approach allows for a more nuanced interpretation of environmental trade-offs and performance across different system configurations.

All modeling and calculations were conducted using SimaPro version 9.5, incorporating background data from the Ecoinvent 3.9.1 database.

- System boundaries and alternative scenarios

The complete biorefinery system modeled in this study comprises two distinct phases: the upstream stage, represented by the WH of *F. lumbricalis* (as described in the preceding section), and the downstream phase, encompassing biomass processing operations. Together, these stages form the system configuration of the CB, which serves as the baseline scenario for environmental performance assessment. The system boundaries align with the process layout illustrated in Figs. 2.2 and 2.3, which delineate the CB workflow from raw biomass collection through product extraction and end-of-life valorization.

To evaluate the influence of specific operational changes on environmental outcomes, four ASs were developed. These scenarios focus on key sustainability drivers, including energy consumption and biomass residue utilization, both of which are central to minimizing the environmental footprint of the system. The alternative scenarios are defined as follows:

1. AS1 evaluates the integration of biogas production as an end-of-life valorization strategy for residual biomass from carrageenan extraction, rather than its

conventional use as a biostimulant. This approach follows the methodology outlined by Fasahati et al. (2022) [72], detailing a two-stage process where biomass undergoes anaerobic digestion to produce biogas, which is subsequently converted into electricity via a boiler/turbogenerator system.

2. AS2 introduces a drying stage in the biorefinery process to prevent biomass degradation and facilitate transportation when immediate processing is not feasible. In this scenario, drying is applied after pigment extraction, based on laboratory findings from Vetik OÜ, which confirm that pigment yield is highest when extracted from fresh *F. lumbricalis*. The drying process is designed to reduce the water content of biomass to 20 %, ensuring optimal preservation while mitigating the risk of degradation. Due to the lack of primary data on drying technology, the modeling was conducted using a standard drying process from the Ecoinvent 3.9.1 database, a methodology also adopted by Seghetta et al. (2016) [24] for drying *S. latissima* biomass.
3. AS3 investigates the adoption of a renewable energy mix instead of relying on Estonia's conventional electricity grid. The Renewable Energy Certificate System (REC) [93] was used as a reference, simulating a scenario where the biorefinery's electricity demand is met entirely by renewable energy sources. The energy mix composition was adapted from Ecoinvent 3.9.1.
4. AS4 explores the feasibility of installing an on-site solar energy system at the biorefinery plant to generate electricity internally, thereby reducing dependence on external power sources and lowering the environmental impact. The scenario incorporates photovoltaic panels and inverters, modeled using data from the Ecoinvent 3.9.1 database.

The system boundaries for SPE and TLE are instead detailed in Figs. 2.6 and 2.7, respectively.

- LCIA

The LCA calculations for this study were carried out using SimaPro v9.5 software employing the ReCiPe2016 impact assessment method (Hierarchist perspective, midpoint, and endpoint levels) [94]. ReCiPe2016 provides a comprehensive framework that includes 18 midpoint indicators, which are systematically categorized under three overarching areas of protection: human health, ecosystems, and resource availability. These categories, extensively described in the full Thesis manuscript, are based on defined damage pathways, allowing for a structured and meaningful interpretation of results across different system configurations.

- LCI

The LCI developed for this study is primarily based on direct data collected from key industrial and research partners involved in the TACO ALGAE project. Vetik OÜ provided empirical data for the WH operations, while NOFIMA contributed pilot-scale data for the downstream biorefinery extraction processes. These primary data sources ensure a high level of representativeness and relevance for modeling the baseline scenario. Where primary data were unavailable, the inventory was supplemented using reliable secondary sources. These

included the Ecoinvent v3.9.1 database and peer-reviewed literature, particularly for components such as biogas production and generic process inputs.

To account for the energy consumption associated with upscaling NOFIMA’s pilot-level biorefinery processes to match the defined FU, standard scaling equations and reference values from the literature were applied [87]. This approach ensured consistency in estimating operational energy demand at an industrially relevant scale. The technical specifications of the machinery used in the modeled biorefinery processes, and the calculation of the scaled consumptions are detailed in the full Thesis manuscript.

The upstream operations associated with the WH of *F. lumbricalis* are identical across all biorefinery system configurations assessed in this study, including the CB, SPE, and TLE models. These operations correspond to the data previously reported in Table 2.1 and remain unchanged throughout the comparative analysis. Similarly, the pre-treatment stage and the overall dimensions of the biorefinery facility are standardized for all configurations to ensure consistency in system modeling.

Table 2.3 compiles the inventory data for both the pre-treatment phases. All values are normalized in accordance with the respective FUs and adjusted based on the lifetime of equipment, where relevant. The dataset reflects the total biomass harvested in 2021 by Vetik OÜ, amounting to 181 tons of FW *F.lumbricalis*, and serves as a representative basis for evaluating system-wide environmental impacts.

Table 2.3

LCI for the pre-treatment and biorefinery plant. This is independent of the design selected. From approbation publication No. 4 [73]

	Category	Material/ component	Input on SimaPro software	Quantity	Unit	Source
Pre-treatment						
<i>Inputs</i>	Raw materials	Water for washing	Tap water {Europe without Switzerland} market for tap water Cut-off, U	7.69E+04	kg	Ecoinvent 3.9.1
<i>Outputs</i>	Waste	From washing	Wastewater, average {Europe without Switzerland} market for wastewater, average Cut-off, U	76.92	m ³	Ecoinvent 3.9.1
Biorefinery plant						
<i>Inputs</i>	Raw materials	Biorefinery plant	Chemical factory, organics {RER} chemical factory construction, organics Cut-off, U	4.00E-07	p	Ecoinvent 3.9.1

The further LCI values vary according to the biorefinery configuration under consideration, as each system exhibits distinct characteristics in terms of resource requirements, energy consumption, and extraction efficiency. These differences directly influence the environmental performance of each model. Table 2.4 presents the detailed LCI for the CB, outlining the material and energy flows associated with this system. The dataset reflects the integrated nature of the CB process, which sequentially valorizes the macroalgal biomass into multiple high-value products. All values have been modeled in alignment with the FU and normalized to reflect system-level performance accurately.

Table 2.4

LCI for the CB. From approbation publication No. 4 [73]

	Category	Material/ component	Input on SimaPro software	Quantity	Unit	Source
1st line (pigment extraction)						
<i>Inputs</i>	Raw materials	Water for mixing	Tap water {Europe without Switzerland} market for tap water Cut-off, U	7,692	kg	Ecoinvent 3.9.1
		Energy	Mixing	Electricity, medium voltage {EE} market for electricity, medium voltage Cut-off, U	338.45	kWh
		Tricanter	Electricity, medium voltage {EE} market for electricity, medium voltage Cut-off, U	153.84	kWh	Ecoinvent 3.9.1
		Centrifuge	Electricity, medium voltage {EE} market for electricity, medium voltage Cut-off, U	153.84	kWh	Ecoinvent 3.9.1
		Microfiltration	Electricity, medium voltage {EE} market for electricity, medium voltage Cut-off, U	38.56	kWh	Ecoinvent 3.9.1
		Ultrafiltration	Electricity, medium voltage {EE} market for electricity, medium voltage Cut-off, U	38.56	kWh	Ecoinvent 3.9.1
<i>Outputs</i>	Raw materials, waste	Wastewater	Wastewater, average {Europe without Switzerland} market for wastewater, average Cut-off, U	7.692	m ³	Ecoinvent 3.9.1
2nd line (protein extraction)						
<i>Inputs</i>	Raw materials	Enzyme	Enzymes {GLO} market for enzymes Cut-off, U	7.35	kg	Ecoinvent 3.9.1
		KOH	Potassium hydroxide {GLO} market for potassium hydroxide Cut-off, U	5.88	kg	Ecoinvent 3.9.1
		Water	Tap water {Europe without Switzerland} market for tap water Cut-off, U	15,344	kg	Ecoinvent 3.9.1
	Energy	Enzymatic extraction	Electricity, medium voltage {EE} market for electricity, medium voltage Cut-off, U	802	kWh	Ecoinvent 3.9.1
		Decantation	Electricity, medium voltage {EE} market for electricity, medium voltage Cut-off, U	230.16	kWh	Ecoinvent 3.9.1
		Centrifuge	Electricity, medium voltage {EE} market for electricity, medium voltage Cut-off, U	17.33	kWh	Ecoinvent 3.9.1
	Microfiltration	Electricity, medium voltage {EE} market for electricity, medium voltage Cut-off, U	154.44	kWh	Ecoinvent 3.9.1	
<i>Outputs</i>	Raw materials, waste	Wastewater	Wastewater, average {Europe without Switzerland} market for wastewater, average Cut-off, U	15.356	m ³	Elementary flow
3rd line (carrageenan extraction)						
<i>Inputs</i>	Raw materials	KOH	Potassium hydroxide {GLO} market for potassium hydroxide Cut-off, U	5.28	kg	Ecoinvent 3.9.1
		Water	Tap water {Europe without Switzerland} market for tap water Cut-off, U	15,144	kg	Ecoinvent 3.9.1
	Energy	Heating	Electricity, medium voltage {EE} market for electricity, medium voltage Cut-off, U	1,897	kWh	Ecoinvent 3.9.1
		Decantation	Electricity, medium voltage {EE} market for electricity, medium voltage Cut-off, U	227	kWh	Ecoinvent 3.9.1

	Category	Material/ component	Input on SimaPro software	Quantity	Unit	Source
		Drying	Electricity, medium voltage {EE} market for electricity, medium voltage Cut-off, U	109.57	kWh	Ecoinvent 3.9.1
<i>Outputs</i>	Emissions to air	Water to air	Water_Air emissions	15,144	kg	Elementary flow
Fertilizers production						
<i>Outputs</i>	Avoided products	Nitrogen fertilizer	Inorganic nitrogen fertiliser, as N {EE} market for inorganic nitrogen fertiliser, as N Cut-off, U	25.84	kg	Ecoinvent 3.9.1
		Potassium fertilizer	Inorganic potassium fertiliser, as K2O {EE} market for inorganic potassium fertiliser, as K2O Cut-off, U	3.06	kg	Ecoinvent 3.9.1
		Phosphorous fertilizer	Inorganic phosphorus fertiliser, as P2O5 {EE} market for inorganic phosphorus fertiliser, as P2O5 Cut-off, U	26.52	kg	Ecoinvent 3.9.1

The use of “electricity, medium voltage” in the modeling reflects the intention to simulate conditions representative of a potential industrial-scale operation.

The complete LCI datasets for the SPE, TLE, and the alternative scenarios (AS1–AS4) are provided in the full Thesis manuscript.

2.3. The life cycle costing

LCC is a comprehensive analytical approach used to evaluate the total financial costs associated with a product, process, or service across its entire life span. Unlike traditional cost assessments that focus solely on upfront investment or production expenditures, LCC accounts for all economic aspects, including operation, maintenance, and end-of-life management. This methodology provides a complete perspective on cost structures, supporting more informed financial planning and decision-making processes [95]. Structurally, the LCC framework mirrors the phases of conventional LCA. The first phase, scope definition, establishes the FU and system boundaries, which serve to delineate the cost elements included in the analysis and ensure result comparability. The second phase involves data collection, focusing on the identification and quantification of costs incurred throughout the life cycle. The third phase, cost analysis, aggregates all financial data to determine the total life cycle cost of the system. This phase enables the evaluation of economic scenarios and supports the identification of cost-efficient alternatives. The final phase, interpretation, focuses on analyzing results to uncover potential savings and optimize financial performance, contributing to strategic resource allocation and investment planning.

The defined LCC framework

At present, no universally recognized framework exists for conducting LCC assessments specifically tailored to macroalgae biorefineries. To address this methodological gap, this Thesis proposes a reproducible LCC framework designed to be applicable across similar research contexts. The LCC methodology developed herein is structured into four macro-steps:

1. Technological scheme definition. This step involves outlining the process configurations under investigation, including the construction of detailed technological flow diagrams and validation of mass balances. In this study, this phase corresponds to the definition of the CB, SPE, and TLE biorefinery models, as described in earlier chapters.
2. Inventorying. This phase focuses on compiling a comprehensive dataset for LCC analysis. It builds upon the LCA inventory by integrating cost-related data necessary for economic modeling. The inventory was managed using a structured Excel-based spreadsheet to facilitate systematic data entry, parameter tracking, and transparency in cost attribution.
3. Economic assessment. Key financial indicators are calculated for each biorefinery configuration. These include return on investment (ROI), net present value (NPV), internal rate of return (IRR), and profit index (PI). These metrics provide a quantitative basis for evaluating the economic performance and profitability of each system.
4. Sensitivity assessment. This final step tests the robustness of LCC results by simulating alternative scenarios that reflect market variability. Adjustments in product pricing, raw material costs, and operational expenditures are modeled to assess their influence on the overall financial viability of the biorefinery configurations.

LCC definition

The primary aim of this LCC study is to evaluate the economic feasibility of five distinct *F. lumbricalis* biorefinery configurations: the CB, three single-product extraction pathways targeting pigments (SPEp), proteins (SPEpr), and carrageenan (SPEc), and the TLE. The assessment seeks to identify the most economically viable system while also pinpointing the key financial parameters influencing each design.

The FU for this analysis is set at the processing of 1,000 and 2,000 tons of DW *F. lumbricalis*. These values reflect both the current biomass harvesting license capacity in Kassari Bay, Estonia (1,000 tons), and a potential future expansion scenario (2,000 tons). Using these reference points allows for scalable analysis and future-oriented planning. Defining the geographic context of the system is essential, as regional conditions directly influence economic variables such as labor costs, land use expenses, and utility rates. For this study, the biorefinery operations are assumed to be located in Estonia. This ensures that the LCC model accurately captures country-specific economic conditions, reinforcing the contextual relevance and precision of the financial evaluation.

- LCI for the economic analysis

The economic life cycle inventories (e-LCI) used in this assessment were derived from the same data framework developed for the LCA. In this case, the original input values, expressed in terms of mass, energy, and volume, were converted into monetary units (EUR) and normalized according to the defined FU. The resulting e-LCI is organized into three key macro-categories to facilitate comprehensive economic evaluation:

- Operating costs. These were quantified using multiple data sources. Publicly available commercial data, including prices for fuel, electricity, and consumables, was obtained from the Orbis database [96]. Additional cost figures were supplied by Vetik OÜ to reflect case-specific conditions. The analysis was framed within Estonia's manufacturing sector under NACE code 20.5 (Other chemical products), and cost impacts were refined using filtered datasets to ensure sectoral relevance. Labor costs were estimated using Teatmik [97], referencing financial data from Estonian seaweed-related enterprises.
- Investments. Capital expenditure estimations were developed in collaboration with Alfa Laval [98], a Swedish company with expertise in separation technologies, heat transfer, and fluid handling. The consultation provided technical guidance on optimal equipment sizing for a processing capacity of 1,000 tonnes of *F. lumbricalis*, with provisions for future scale-up to 2,000 tons.
- Product sales. The revenue model was constructed based on a market analysis of comparable commercial products. Pigment pricing was aligned with phycocyanin rather than phycoerythrin due to limitations in purity and processing capabilities within the studied biorefinery system. Protein was priced according to the value of soy-based protein feeds commonly used in animal nutrition. Carrageenan pricing was benchmarked against gelling agents widely used in the cosmetics sector. The residual biomass, no longer viable for use as fertilizer due to depleted mineral content post-extraction (as demonstrated by laboratory findings from the TACO ALGAE project), was assigned a minimal value and sold to biogas producers. This solution not only generated marginal revenue but also reduced the costs associated with waste disposal and treatment.

The complete inventories for the various biorefinery configurations are comprehensively reported in the full Thesis manuscript. For reference, they follow the same structural layout as the LCI presented in Table 2.4; however, instead of mass, volume, and energy inputs, the values are expressed in monetary terms to support the economic assessment.

- Economic analysis parameters

The economic analysis began by defining a set of fundamental financial parameters, which play a critical role in shaping the final results of the LCC model. These include the balance between equity and external loan financing, the expected return on equity, and the applicable interest rate on borrowed capital. These values were selected based on average financial data obtained from the Orbis database: share of investment covered by equity (70 %), remaining share of investment via loans (30 %), required return on equity (10 %), and interest rate for the external loan (4.25 %). Once these parameters were established, the financial modeling proceeded with the calculation of key metrics over a 10-year period to assess the cost-effectiveness of each biorefinery scenario. The analysis included investments, depreciation, inbound cash flows, outbound cash flows, taxable income, taxes, net cash flows, and discounted cash flows. Future cash flows were adjusted to present-day value using the weighted average cost of capital (WACC), which accounts for the time value of money. The WACC was determined as:

$$WACC = (EV \times Re) + (DV \times Rd \times (1 - Tc)) \quad (2.1)$$

To evaluate and compare the financial performance of each scenario, four key economic indicators were applied:

- ROI – the ratio of cumulative net profit to the total investment cost. Higher ROI values indicate more favorable investment scenarios.
 - IRR – the discount rate at which the NPV equals zero. It reflects the efficiency and profitability of the investment, with higher IRR values signaling more desirable opportunities.
 - NPV – the total value of all future cash flows, discounted to present terms and adjusted for the initial investment. A positive NPV indicates a profitable investment.
 - PI – the ratio of NPV to the initial investment represents the value generated per unit of investment. A PI greater than 1 suggests that the project is expected to create financial value.
- Alternative scenarios

The sensitivity analysis conducted in this study focuses on the primary source of uncertainty in the economic assessment: the product market prices. Among the various outputs of the biorefinery system, pigments represent the highest-value product, exerting a substantial influence on the overall financial performance of the biorefinery configurations. As such, pigment price variability was selected as the central parameter for sensitivity testing. A range of pigment prices was established through market research, allowing for the development of benchmark scenarios to evaluate the system's economic robustness under different pricing and production conditions. In addition to the intermediate reference scenario, where the pigment price was set at 124,736 €/ton (as reported in Table 2.5), two additional scenarios were modeled:

- Worst case scenario (WCS). This scenario assumes the lowest market valuation for pigment, set at 100,000 €/tons, paired with the current harvesting limit of 1,000 tons of *F. lumbricalis*. It represents a conservative outlook, reflecting limited market demand and constrained biomass availability.
 - Best case scenario (BCS). This scenario considers a high-value market context, with the pigment price reaching 500,000 €/tons. It is coupled with the maximum harvesting capacity allowed under extended licensing (2,000 tons of *F. lumbricalis*), simulating a favorable regulatory and market environment for scale-up.
- Monetization of environmental externalities for the LCC

To further enhance the comprehensiveness of the economic evaluation, this Thesis integrates the monetization of environmental externalities derived from the LCA of the same system. This added dimension introduces a novel approach to cost analysis by translating environmental impacts into economic terms, thus providing a novel view of the system's sustainability. The methodology adopted is based on the framework proposed by Ponsioen et al. (2020) [99], which offers conversion factors to express LCA results in monetary units. These factors (detailed in the full Thesis manuscript) are compatible with both midpoint and endpoint impact categories under the ReCiPe 2016 method; the same impact assessment framework used in the LCA component of this research. When both midpoint and endpoint values are available,

midpoint monetization factors are prioritized to improve the precision and consistency of the assessment.

2.4. The social life cycle assessment

Since the 1960s, growing awareness of the limitations of unchecked economic and industrial growth within the boundaries of a finite planet has led to the emergence of the concept of sustainable development. This principle emphasizes the need to meet current human needs without compromising the ability of future generations to meet theirs. Sustainability, as outlined in global frameworks such as the United Nations Sustainable Development Goals, encompasses not only environmental concerns but also social dimensions. This broader understanding has prompted the evolution of LCA into S-LCA, a methodology designed to evaluate the social impacts of products and systems throughout their life cycle [95]. S-LCA follows a structural framework similar to environmental LCA, comprising the key phases of goal and scope definition, inventory analysis, impact assessment, and interpretation. However, S-LCA is concerned with the effects of products and processes on human well-being. It assesses these impacts across multiple stakeholder groups, including workers, local communities, consumers, and decision-makers, aiming to capture the social implications of systems and their contributions to societal sustainability.

Despite its conceptual alignment with LCA, S-LCA remains in a developmental phase and lacks the standardization that environmental LCA has achieved. The most significant effort toward harmonization came with the publication of the UNEP-SETAC Guidelines for S-LCA initiative [100], which established a foundational methodological structure. More recently, the release of ISO 14075, titled “Environmental Management – Principles and Framework for Social Life Cycle Assessment” [101], marked an important milestone toward formal recognition of the methodology. Nevertheless, key challenges remain, particularly regarding the consistent definition and quantification of social impacts.

In S-LCA, the primary area of protection is human well-being. Assessments aim to characterize social change induced by a product or process and to determine whether these changes contribute positively or negatively to broader sustainability goals. Stakeholders typically include supply chain workers, local or regional communities affected by production activities, and end consumers. Additional actors, such as company shareholders and policy-makers, may also be included when relevant to the system under analysis.

As the global discourse on social sustainability advances, S-LCA offers a critical framework for incorporating social dimensions into sustainability assessments. However, further methodological refinement is necessary to enhance its reliability and utility in policy and investment decision-making.

In response to these challenges, this Thesis proposes a hybrid methodology that integrates recent advancements in S-LCA, offering a comprehensive and contemporary framework tailored to the *F. lumbricalis* biorefinery system.

The methodological framework for the S-LCA

The S-LCA conducted in this work adopts a dual-scale approach, consistent with established practices in the literature [102]. This multi-level framework enables a more comprehensive and context-sensitive evaluation of potential social impacts, ensuring broader indicator coverage than would be possible through a single-scale analysis.

1. Impact pathway approach (IPA) – Scale 1. This macro-level assessment is conducted at the national scale and is used to perform a social hotspot analysis. Its primary objective is to identify significant potential social risks associated with the macroalgae sector, with a particular focus on WH and OFC. The IPA is based on causal-effect chains that link quantitative inventory indicators to broader social damage categories. This top-down methodology is implemented using the Social Hotspot Database (SHDB) [103] integrated within the SimaPro software platform. The IPA allows for the systematic identification of social “hotspots” within the modeled product system, supporting early-stage risk detection and strategic mitigation planning.
2. Reference scale approach (RSA) – Scale 2. The second scale targets the micro-level, providing a detailed assessment of individual companies and their operations. This small-enterprise focus allows for a more granular analysis of organizational performance, offering insights that cannot be captured at the macro scale. Social impacts are evaluated using performance reference points (PRPs), which are benchmarked against internationally recognized standards, thresholds, or best practices. The evaluation follows a semi-quantitative 0–5 scoring scale, tailored to the specific characteristics of the *F. lumbricalis* biorefinery system. Custom questionnaires will be developed to collect data from relevant stakeholders, supporting a robust and enterprise-specific assessment.

The IPA framework

The IPA adopted in this study follows a methodological structure analogous to that of traditional environmental LCA. It incorporates the standard phases of goal and scope definition, system boundary delineation, inventory analysis, and LCIA.

- Goal and scope

The primary objective of this assessment is to investigate the social dimensions embedded within macroalgae value chains, beginning with the biomass collection phase. The analysis employs S-LCA to evaluate and compare the social impacts associated with different harvesting and cultivation techniques for macroalgae. Specifically, the research focuses on identifying key social issues linked to the WH of the red macroalga *F. lumbricalis*, serving as the reference scenario. WH was selected for this analysis given its status as the predominant collection method for this species and its limited representation in existing literature. This reference case aligns with the system boundaries outlined in Section 2.1.

In addition to the WH baseline, the study includes an exploratory scenario involving a hypothetical OFC system for *F. lumbricalis*. Although not yet operational at a commercial scale, this scenario was constructed using literature data [70] to assess the potential social

implications of implementing such a system. To ensure methodological consistency and comparability between scenarios, the FU is defined as 1 USD generated during a standard 8-hour working day. This FU reflects the unique economic structure of each system and aligns with the requirements of the SHDB, which uses monetary-based inputs for its assessments.

- System description in the context of SHDB

The WH system follows the same process structure detailed in Section 2.1. For the purpose of the S-LCA and within the defined FU, the total amount of *F. lumbricalis* harvested is 10 tons of fresh biomass. In parallel, the OFC scenario was modeled using literature-based data, particularly from studies on artificial substrate cultivation for *F. lumbricalis*. All inventory data were normalized to match the 10-ton biomass yield of the WH scenario to ensure consistency in comparative assessment. Figure 2.8 provides a schematic overview of the OFC configuration.

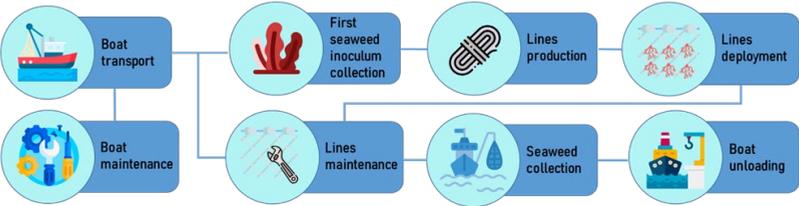


Fig. 2.8. System diagram for the OFC scenario.

To identify potential social risks, the SHDB was integrated into the S-LCA model. The SHDB aggregates social risk data from organizations such as the International Labor Organization and the World Bank, assessing indicators related to child labor, forced labor, wages, health and safety, and working conditions. A total of 30 social issues were evaluated in this study. As a well-established tool, the SHDB applies a risk-based approach across more than 150 sectors in nearly 200 countries, enabling consistent hotspot identification within supply chains. In this assessment, SHDB processes were selected to reflect the specific sectoral activities taking place in Estonia, in alignment with the defined system boundaries. A detailed listing of these processes is reported in the full Thesis manuscript. In cases where direct process matches were unavailable, suitable proxy processes were applied. For example, operations such as boat unloading and vessel maintenance were modeled using broader manufacturing and trade-related categories.

- LCI

Table 2.6 presents the LCI for the WH scenario, providing a detailed overview of the operational stages, associated allocation factors, and the underlying assumptions used in their calculation. The allocation factors were derived by analyzing the specific operational characteristics of each process step, considering aspects such as time requirements, resource consumption, and logistical constraints.

Table 2.6

LCI for the WH scenario				
Stage	Description	Assumption/ calculation	Daily time to perform the operation	Allocation to FU
<i>Seaweed harvesting</i>	Harvesting by throwing. 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 %
<i>Transport to harbor</i>	40 minutes of sailing distance	Considered 2 times, to go and come back	1.33 hours	17 %
<i>Boat unloading</i>	Electric unloader	-	1.50 hours	19 %
<i>Boat maintenance</i>	1 time per year (1 month)	Normalization of the 1-month period to the 8 hours of FU	0.67 hours	8 %

Table 2.7 summarizes the LCI for the OFC scenario. The initial data were mapped across the three-month cultivation period required to achieve a biomass yield of 10 tons of *F. lumbricalis*. To ensure methodological consistency with the WH scenario, all values were subsequently normalized to the defined functional unit.

In both WH and OFC scenarios, the LCI is harmonized by expressing all calculations in terms of total work hours performed. This approach facilitates a direct and equitable comparison between the systems, shifting the analytical focus toward the social risks experienced by individual workers across different operational contexts.

Table 2.7

LCI for the OFC scenario					
Stage	Description	Assumption/calculation	Time to perform the operation (3 months)	Normalization on the FU	Allocation to FU
<i>Boat transport</i>	40 minutes of sailing distance	It includes boat transport for the first seaweed inoculum collection, for the lines' deployment, line maintenance, and for the final seaweed collection.	1.33 hours (for 1 single trip, to and fro)	0.24 hours	2.96 %
<i>First seaweed</i>	603 kg are needed to	It has been calculated, knowing the rate and the	6.00 hours (for all the trips)	0.020 hours	0.25 %

Stage	Description	Assumption/calculation	Time to perform the operation (3 months)	Normalization on the FU	Allocation to FU
<i>inoculum collection</i>	obtain 10,000 kg of fresh <i>F. lumbricalis</i>	time of growth, and the final target amount			
<i>Lines production</i>	Nylon mesh bags	The amount of nylon required was calculated by normalizing data from the literature [24], 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 [104], and this value was normalized to match the 33 kg required for the system	1.06 hours	0.042 hours	0.52 %
<i>Lines deployments</i>	-	Assumed half of the time needed for the seaweed collection	2.25 hours	0.089 hours	1.11 %
<i>Lines maintenance</i>	1 time per month	3 times in total. It is assumed that the same time is needed for the line deployment	6.75 hours	0.27 hours	3.33 %
<i>Seaweed collection</i>	-	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 %
<i>Boat unloading</i>	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 %
<i>Boat maintenance</i>	1 time per year (1 month)	Normalization of the 1-month period to the 3-month period needed for the seaweed growth	180 hours	7.11 hours	88.86 %

- LCIA

The LCIA in this analysis was performed using the Social Hotspot 2022 Category Method w Norm, integrated within the SHDB module of the SimaPro v9.5 software. A detailed representation of the methodology is illustrated in the full Thesis manuscript. This method is based on the Social Hotspot 2022 Subcategory Method w Norm/Global per Capita Annual, which includes 30 social risk subcategories grouped into five overarching damage categories [105].

The characterization process involves multiplying the LCI results by predefined risk probability factors, which reflect the likelihood of adverse social conditions, such as poor labor

standards or community-level vulnerabilities, associated with each subcategory. The outcomes are expressed in medium risk-hour equivalents (mrheq), a unit that quantifies social risks based on the probability and severity of occurrence. Following subcategory classification, the results are aggregated into damage categories using a weighted sum approach. This ensures that the final scores reflect relative risk without being distorted by the number of subcategories within each category. The method also incorporates normalization at the category level and allows for optional user-defined weighting. Final results are expressed in standardized units known as social points (S-Pt), which represent annual per capita medium risk-hour equivalents relative to global economic output. This normalization enables meaningful comparison of social risks across sectors and product systems, enhancing the robustness of the analysis.

- **Uncertainty analysis**

Significant uncertainties remain associated with both defined scenarios. As this represents the first application of S-LCA to macroalgae harvesting and production systems, the modeled configurations retain a hypothetical character, leading to uncertainty in several key parameters. This is particularly relevant for the allocation factors, which estimate the time requirements for each operational phase described in Figs. 2.2 and 2.8.

To account for these uncertainties, a Monte Carlo simulation was performed using the SimaPro software environment. The simulation adopted a normal distribution to vary initial input values across a defined uncertainty range, running a total of 5,000 iterations. The variability range for each parameter was determined based on its relative importance and the level of uncertainty associated with its definition. Within the WH scenario, seaweed harvesting emerged as the most uncertain stage, primarily due to operational variability under open-sea conditions. In the OFC scenario, greater uncertainty was observed in the first seaweed inoculum collection, seaweed collection, line deployment, and line maintenance activities that are especially susceptible to environmental fluctuations such as weather conditions. A larger uncertainty margin of $\pm 30\%$ was therefore applied to these operations. Intermediate variability ($\pm 20\%$) was assigned to boat maintenance and unloading, reflecting their general predictability but accounting for potential fluctuations due to vessel usage frequency and operational intensity. In contrast, a lower uncertainty range ($\pm 10\%$) was assigned to more stable operations, such as transport to the harbor and line production, which are less sensitive to external factors.

The RSA framework

At the small-enterprise level, no standardized databases currently exist to capture the full scope of potential social risks associated with the macroalgae sector. To address this gap, direct primary data collection was undertaken through the development of two custom-designed questionnaires specifically tailored for this study and reported in the Thesis appendices. The assessment framework was built in accordance with the UNEP Social LCA Handbook [100] and the ISO 14075 [101], ensuring methodological consistency with international best practices.

The first questionnaire served as a broad screening tool to identify the most relevant social indicators and stakeholder groups. It included a wide-ranging list of stakeholder categories and social performance indicators based on the UNEP framework. This initial

survey was circulated among project partners in the TACO ALGAE consortium for review and validation. Based on the responses, nine subcategories and four stakeholder groups were identified as the most relevant for the macroalgae biorefinery system (Table 2.8).

These findings informed the development of the second questionnaire, which focused exclusively on the selected indicators. This follow-up instrument included 14 questions organized around the two primary stages of the macroalgae value chain: biomass collection or cultivation, and biomass processing. The second questionnaire was distributed to a targeted panel of eight experts. The responses were qualitatively assessed and classified according to a four-tier risk scale: high, medium, low, or zero risk. To support a more structured and quantitative interpretation of the results, a reference scale (RS) was introduced, converting qualitative responses into numerical scores ranging from -2 (high risk) to +2 (no risk). A color-coded scheme was also incorporated to enhance visual clarity and interpretability. As an example of RS, the *health and safety* indicator of the workers is reported in Table 2.8. For all the other indicators, the RSs are detailed in the full Thesis manuscript.

Table 2.8

Selected indicators to define the potential social impacts for each category of stakeholder

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

Table 2.9

RS for the health and safety indicator for 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/damage 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/damage 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 of the processes under analysis to be exposed to accidents/damage to health and safety, as well as to carry out strenuous activities.
-2	There is a very high risk for workers in the processes under analysis to be exposed to accidents/damage to health and safety, as well as to carry out strenuous activities.

2.5. The life cycle sustainability assessment

LCSA is a comprehensive framework that integrates LCA, LCC, and S-LCA assessments to evaluate the overall sustainability performance of products, processes, or systems. By addressing the three pillars of sustainability simultaneously, LCSA enables decision-makers to identify trade-offs and synergies, ensuring that improvements in one area do not lead to unintended negative consequences in another. First conceptualized by Walter Klöpffer [106], LCSA emphasizes the interpretation of indicators in a comparative and integrative manner rather than combining them into a single aggregated score. This integrative approach supports a nuanced understanding of how different sustainability aspects interact, enhancing the ability to make informed, balanced decisions. The adoption of LCSA provides several practical benefits. It supports structured data management, clarifies complex sustainability trade-offs, and aids in identifying strengths and weaknesses within production systems. It enables organizations to enhance supply chain transparency, improve product design, and prioritize sustainable innovations. From a policy perspective, LCSA serves as a foundation for developing eco-labeling schemes, sustainability certifications, and responsible consumption policies.

To support the application of LCSA, a multi-criteria decision analysis (MCDA) approach is often adopted. MCDA provides a structured methodology for comparing alternatives based on multiple indicators, drawing from fields such as engineering, economics, and social sciences. Several MCDA methods are available, offering different levels of detail and decision-making logic. Among these, the technique for order preference by similarity to ideal solution (TOPSIS) [107] has emerged as a particularly relevant tool in sustainability studies, due to its capacity to identify the alternative closest to the optimal balance across all impact categories.

The TOPSIS methodology

To support decision-making within the LCSA, the TOPSIS method was employed. Recognized for its clarity, minimal data requirements, and intuitive results, TOPSIS provides a systematic framework for ranking multiple alternatives based on their proximity to an ideal solution [107]. TOPSIS operates on the principle of identifying the best-performing option as the one closest to the ideal solution and furthest from the anti-ideal. The method relies on a weighted comparison of alternatives across a set of defined criteria. While it introduces a subjective component through weight assignment, this step is essential for capturing the relative importance of each criterion in the decision-making process.

The computational structure of TOPSIS consists of six sequential steps. First, a decision matrix is built to record the performance of each alternative across the chosen criteria. Next, the data are normalized to enable comparison across different units of measurement. The normalized values are then multiplied by their corresponding weights, producing a weighted matrix. From this matrix, the ideal and anti-ideal solutions are identified, representing the best and worst values achievable for each criterion. The Euclidean distances of each alternative from both of these reference points are then calculated. Finally, a closeness coefficient is determined

for each alternative, expressing how close it is to the ideal solution on a scale from 0 to 1. The alternative with the highest score is considered the most sustainable option.

Data integration for the LCSA

To evaluate the overall sustainability of the three biorefinery configurations, CB, SPE, and TLE, an MCDA approach was adopted within the LCSA framework. The assessment was structured around the three pillars of sustainability: environmental, economic, and social, each represented by four specific sub-criteria, resulting in a total of twelve evaluation indicators.

Environmental indicators were derived from the LCA results presented in Section 3.1, focusing on key impact categories where the systems demonstrated the most significant differences. These included global warming potential, particulate matter formation, human toxicity, and water consumption.

Economic indicators were based on the LCC outcomes from Section 3.2, encompassing ROI, NPV, IRR, and PI. For comparability, the SPE system was evaluated as a full configuration by including its three product lines: SPE_p, SPE_{pr}, and SPE_c.

Social indicators were selected to reflect the most meaningful differences between the biorefinery designs, using results from the S-LCA in Section 3.3. These included: *health and safety* of workers (HS), *working hours* of workers (WHS), *local economic development* (LED), and *wealth distribution* (WD). Adjustments were made to ensure comparability between systems. The full equations defined are reported in the Thesis manuscript.

To assign weight to the three sustainability pillars, a distributive normalization method was applied, initially assigning equal importance (33 %) to each pillar. This balanced approach ensured a fair evaluation of environmental, economic, and social impacts. To explore the influence of different weighting strategies, a sensitivity analysis was conducted by progressively increasing the weight of each pillar while proportionally adjusting the others. The weight adjustments were tested at different intervals, ranging from 10 % to 300 %, to examine how changes in priority influence the final sustainability ranking of the biorefinery configurations.

3. RESULTS AND DISCUSSION

3.1. Environmental results

Results of the LCA on the different techniques for the upstream stage

This section presents a comparative environmental evaluation of three macroalgae production methods: WH, ONC, and OFC. These systems are detailed in Section 2.1 (Fig. 2.2) and Section 2.2 (Figs. 2.6 and 2.7). The focus of this summary is on the full environmental results of the WH system, alongside a comparative overview of all three scenarios. Complete results for ONC and OFC are available in the full Thesis manuscript.

- WH results

Table 3.1 summarizes the environmental impact results for the WH scenario across the selected midpoint indicators. Within the table, the process step with the highest environmental burden is highlighted in grey, emphasizing the most critical stage in terms of sustainability performance.

Table 3.1

Midpoint results for the WH scenario. From approbation publication No. 2 [71]

Impact category	Unit	Seaweed harvesting	Transport to the harbor	Unloading the boat	Final transport
CC	kg CO ₂ eq	6.79E+01	4.53E+00	5.99E-01	1.14E+01
PM	disease inc.	6.33E-06	1.20E-06	5.19E-08	8.60E-07
AP	mol H ⁺ eq	8.36E-01	1.60E-01	5.53E-03	4.54E-02
EF	kg P eq	1.54E-02	4.75E-05	4.26E-05	8.45E-04
EM	kg N eq	2.01E-01	3.87E-02	8.16E-04	1.32E-02
ECF	CTUe	1.63E+03	3.30E+01	7.00E+00	1.39E+02
LU	Pt	1.56E+02	7.87E+00	3.81E+00	1.02E+02
WU	m ³ depriv.	2.57E+01	1.09E-02	4.43E-02	6.05E-01
RF	MJ	8.32E+02	6.22E+01	8.21E+00	1.70E+02
RM&M	kg Sb eq	2.81E-03	8.15E-07	8.08E-07	4.72E-05

Note: CC (climate change), PM (particulate matter), AP (acidification potential), EF (eutrophication freshwater), ECF (ecotoxicity freshwater), LU (land use), WU (water use), RF (resource use fossil), and RM&M (resource use minerals & metals)

Figure 3.1 highlights that the seaweed harvesting phase is the dominant contributor to the overall environmental impact in the WH scenario, with particularly high effects observed in the RM&M and CC indicators. The results are expressed in EcoPoints (Pt), offering a single-score representation normalized against the annual environmental footprint of an average EU citizen [108], thus allowing for intuitive comparison across impact categories.

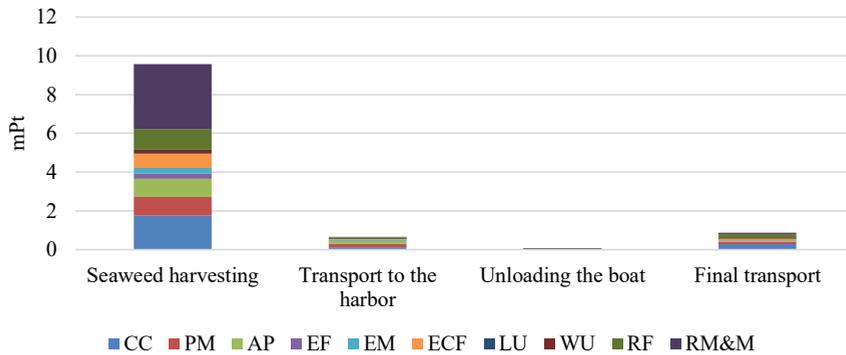


Fig. 3.1. Endpoint results for the WH. From approbation publication No. 2 [71].

Figure 3.2 offers a breakdown of the environmental impacts associated with the seaweed harvesting process. The antifouling agent emerges as the most significant contributor, with an impact of 3.18 mPt, followed by diesel fuel at 2.28 mPt, and steel used for boat construction and maintenance at 1.45 mPt. These findings underline the main sources of environmental pressure within the harvesting phase, pointing to key areas for potential improvements, such as adopting eco-friendly antifouling agents, enhancing fuel efficiency, or exploring alternative boat construction materials.

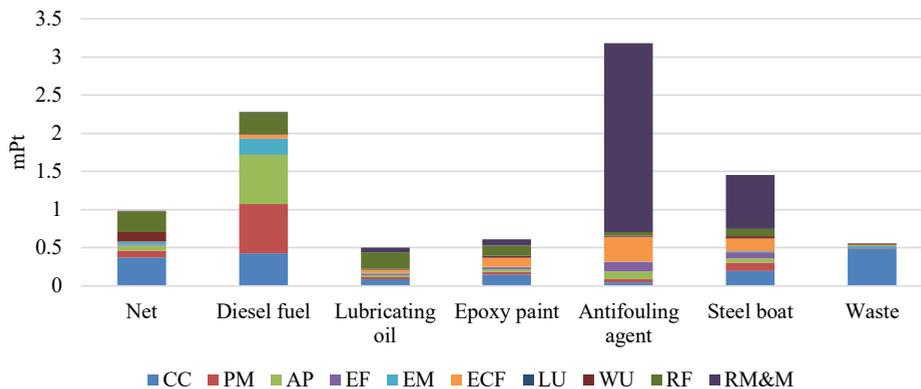


Fig. 3.2. Focus results for the seaweed harvesting procedures in the WH system. From approbation publication No. 2 [71].

- Comparison of the three scenarios

Table 3.2 presents the total environmental impact results across all midpoint indicators, emphasizing the most impactful values for each macroalgae production scenario. The ONC system shows the highest impacts on CC, EF, ECF, land use (LU), and water use (WU). The OFC system leads in PM, AP, EM, and RF. In contrast, the WH scenario demonstrates the greatest burden in RM&M.

Table 3.2

Total midpoint results of the WH, ONC, and OFC scenarios. From approbation publication No. 2 [71]

Impact category	Unit	WH total	ONC total	OFC total
CC	kg CO ₂ eq	8.45E+01	2.20E+02	2.60E+02
PM	disease inc.	8.45E-06	1.28E-05	1.08E-05
AP	mol H ⁺ eq	1.05E+00	8.47E-01	3.07E+00
EF	kg P eq	1.63E-02	7.00E-02	2.68E-02
EM	kg N eq	2.54E-01	2.08E-01	7.82E-01
ECF	CTUe	1.81E+03	7.86E+04	2.23E+03
LU	Pt	2.69E+02	4.77E+04	6.67E+02
WU	m ³ depriv.	2.64E+01	1.15E+02	1.34E+02
RF	MJ	1.07E+03	2.08E+03	4.80E+03
RM&M	kg Sb eq	2.86E-03	2.27E-03	9.13E-04

Note: CC (climate change), PM (particulate matter), AP (acidification potential), EF (eutrophication freshwater), ECF (ecotoxicity freshwater), LU (land use), WU (water use), RF (resource use fossil), and RM&M (resource use minerals & metals)

The results presented in Table 3.2 are further illustrated in Fig. 3.3, which depicts the normalized environmental impacts of the three macroalgae production systems. ONC shows the highest overall impact, with a total of 56.206 mPt, followed by OFC at 22.76 mPt, and WH at 11.10 mPt, confirming WH as the most environmentally favorable option. In the ONC scenario, the most impactful indicators were ECF with 35.22 mPt and CC with 5.73 mPt. For OFC, the greatest contributions came from CC (6.77 mPt) and RF (6.14 mPt). In the WH scenario, the main drivers of impact were RM&M at 3.39 mPt and CC at 2.20 mPt.

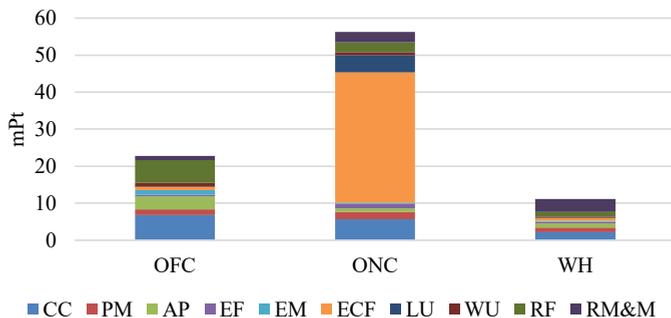


Fig. 3.3. Total endpoint comparison between WH, ONC, and OFC scenarios. From approbation publication No. 2 [71].

- Comparison including the ASs

Figure 3.4 offers a comparative overview of the baseline systems and all alternative scenarios, highlighting the variations in environmental performance across different configurations. For the WH scenario, the most significant improvement is seen in WH_AS3, where the adoption of a less harmful antifouling agent reduces the environmental impact by 28.02 %. Conversely, WH_AS4, which focuses on reducing diesel consumption, results in only a modest 2.07 % decrease. In the OFC scenario, both OFC_AS1 and OFC_AS4 deliver limited

improvements. Notably, the integration of solar panels slightly increases environmental burdens due to the material requirements for panel construction, outweighing the benefits from reduced electricity use. It is also important to note that the assessment does not consider the carbon sequestration or nutrient removal potential of seaweed, as also observed in the reference study by Seghetta et al. (2016) [24]. However, recent literature indicates that accounting for these benefits may significantly enhance the environmental profile of OFC systems [109]. For the ONC scenario, replacing artificial lighting with natural sunlight in ONC_AS2 yields the most substantial benefit, achieving a 78.25 % reduction in impact, bringing the results nearly in line with those of WH. ONC_AS1, which introduces solar power, achieves a 26.9 % reduction, though still limited by the environmental cost of solar panel production. A further sensitivity analysis shows that substituting geothermal power with the Icelandic national energy mix, which includes 71 % hydropower, would reduce the ONC baseline impact by 35.28 %, suggesting that geothermal energy may not be the optimal solution for minimizing environmental impacts in this context.

Among all configurations, the WH_AS3 scenario demonstrates the lowest environmental impact, achieving a total of 7.99 mPt by replacing the conventional antifouling agent with a less hazardous alternative. In contrast, the highest impact is recorded in the baseline ONC scenario, with a total of 56.21 mPt. The most substantial reduction in environmental burden is observed in ONC_AS2, where the replacement of artificial lighting with natural sunlight results in a 78.25 % decrease. However, this improvement must be viewed with caution, as the feasibility of this solution in Iceland, where sunlight availability is limited, is questionable. Nonetheless, the scenario may offer promising results for lower-latitude regions with greater solar exposure. In the WH system, the analysis is based on a favorable geographic context, with the harvesting area located just 40 minutes from the harbor. In less optimal locations, longer transport distances could considerably increase the environmental burden, particularly given that diesel fuel is the second most impactful factor in this scenario.

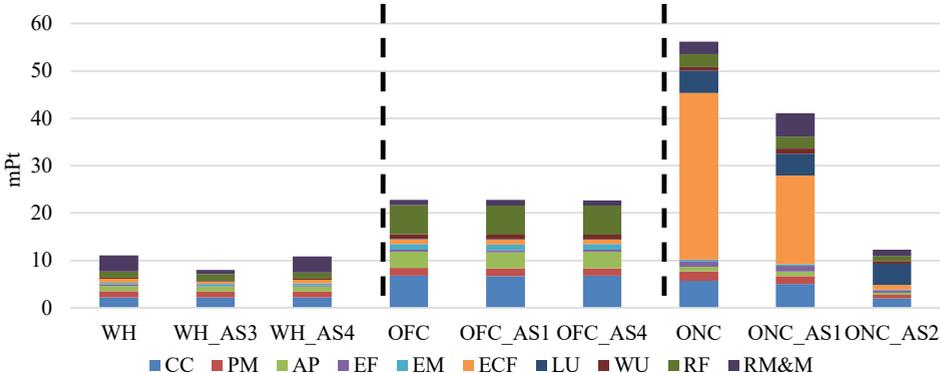


Fig. 3.4. Comparison of the baseline and alternative scenarios. AS1 – 50 % solar panel plant energy. AS2 – natural sunlight instead of artificial light. AS3 – environmentally friendly antifouling agent. AS4 – reduced diesel consumption of boats by 10 %. From approbation publication No. 2 [71].

Results of the LCA on the full biorefinery system

- CB hot-spot results

Table 3.3 reports the environmental impact results for the CB system, expressed in midpoint impact categories and normalized to FU1. In this context, positive values indicate environmental burdens, while negative values reflect avoided impacts, meaning the system contributes to mitigating specific environmental pressures. The results are color-coded, with a gradient from dark red (high impact) to light green (low impact), providing a clear visual interpretation of the system’s performance across various stages. The extraction phases of the biorefinery are identified as the most environmentally demanding, with the carrageenan recovery stage representing the highest contribution to overall impacts. In contrast, the final phase, where residual biomass is repurposed as a biostimulant fertilizer, shows environmental benefits, reflected by its negative impact score. To corroborate these outcomes, Fig. 3.5 presents the endpoint results in a normalized and weighted format, helping to pinpoint the stages with the greatest environmental significance.

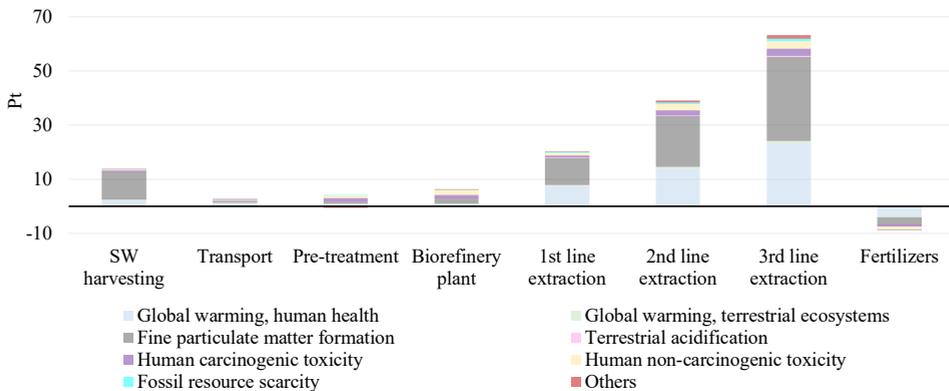


Fig. 3.5. Endpoints normalized and weighted results for the CB baseline scenario considering FU1. Note that “others” include all the other indicators contributing < 1 % to the total impact. From approbation publication No. 4 [73].

The total environmental burden associated with the CB system is estimated at 140.08 Pt. Among the impact categories, PM and GWP emerge as the most critical, accounting for 70.22 Pt and 46.02 Pt, respectively. These impacts are primarily linked to the energy-intensive processes of biomass extraction and diesel consumption during harvesting. Within the extraction phases, the third processing line dedicated to carrageenan recovery stands out as the most impactful stage (63.28 Pt), followed by the protein extraction line (39.09 Pt). In the upstream WH phase, diesel fuel use (11.8 Pt) and the steel required for boat construction (0.65 Pt) are the main contributors. These findings differ slightly from those in previous analyses due to updates in the LCIA methodology and the Ecoinvent database, which have altered impact characterizations over time. The adoption of more efficient engines or cleaner fuel alternatives could help mitigate these impacts. Notably, the production of fertilizer from residual biomass demonstrates a positive environmental effect, offsetting 8.82 Pt by displacing conventional market fertilizers.

Table 3.3

Midpoint results for the CB, baseline scenario, considering FU1. From approbation publication No. 4 [73]

	Unit	SW harv.	Trans.	Pre-treat.	Bio. plant	1st line	2nd line	3rd line	Fert.	Total
GWP	kg CO ₂ eq	1.56E+02	7.87E+01	5.38E+01	5.51E+01	4.82E+02	9.02E+02	1.49E+03	-	2.97E+03
SOD	kg CF C11 eq	1.39E-04	3.82E-05	1.33E-04	2.28E-05	3.35E-04	9.04E-04	1.00E-03	5.33E-04	2.04E-03
IR	kBqCo-60 eq	2.76E+00	1.26E+00	1.25E+01	8.29E+00	8.77E+01	1.58E+02	2.70E+02	1.40E+01	5.26E+02
OFhh	kg NO _x eq	2.93E+00	2.38E-01	1.28E-01	1.77E-01	1.61E+00	3.00E+00	4.98E+00	4.21E-01	1.26E+01
PM	kg PM _{2.5} eq	9.56E-01	6.92E-02	7.41E-02	1.88E-01	9.50E-01	1.78E+00	2.94E+00	2.60E-01	6.70E+00
OFt	k NO _x eq	2.95E+00	2.54E-01	1.33E-01	1.83E-01	1.72E+00	3.19E+00	5.32E+00	4.52E-01	1.33E+01
TA	kg SO ₂ eq	3.01E+00	1.48E-01	1.76E-01	4.74E-01	2.37E+00	4.67E+00	7.34E+00	1.02E+00	1.72E+01
EF	kg P eq	2.41E-02	5.92E-03	2.17E-01	6.21E-02	1.17E-01	2.59E-01	3.02E-01	5.16E-02	9.34E-01
ME	kg N eq	4.86E-03	2.11E-03	3.58E-01	2.69E-03	4.97E-02	2.10E-01	4.37E-02	1.97E-02	6.51E-01
TE	kg 1,4-DCB	1.89E+02	1.24E+03	2.26E+02	2.74E+03	1.53E+03	3.13E+03	4.73E+03	1.55E+03	1.22E+04
ECF	kg 1,4-DCB	3.02E+00	1.92E+00	3.78E+00	3.24E+01	9.18E+00	2.22E+01	2.83E+01	1.48E+01	8.59E+01
MEc	kg 1,4-DCB	4.06E+00	3.23E+00	5.13E+00	4.18E+01	1.28E+01	2.84E+01	3.94E+01	1.91E+01	1.16E+02
HCT	kg 1,4-DCB	8.37E+00	3.91E+00	2.47E+01	2.50E+01	1.66E+01	3.43E+01	4.85E+01	1.43E+01	1.47E+02
HNCT	kg 1,4-DCB	8.53E+01	6.13E+01	2.81E+02	5.01E+02	2.47E+02	5.98E+02	6.99E+02	2.42E+02	2.23E+03
LU	m ₂ a crop eq	2.49E+00	3.13E+00	1.36E+00	5.83E+00	3.86E+01	1.19E+02	1.19E+02	8.83E+00	2.81E+02
MRS	kg Cu eq	4.89E-01	2.04E-01	5.06E-01	2.62E+00	5.78E-01	1.44E+00	1.75E+00	3.56E+00	4.03E+00
FRS	kg oil eq	4.99E+01	2.48E+01	1.19E+01	1.30E+01	1.41E+02	2.59E+02	4.38E+02	7.21E+01	8.66E+02
WU	m ³	4.91E-01	1.56E-01	1.47E+01	6.37E-01	1.87E+00	1.20E+01	2.53E+01	3.55E+00	2.23E+01

Note: SW harv. (seaweed harvesting), trans. (transportation), Bio. plant (biorefinery plant), 1st line (pigment extraction), 2nd line (protein extraction), 3rd line (carrageenan extraction), fert. (fertilizers)

GWP (global warming), SOD (stratospheric ozone depletion), IR (ionizing radiation), OFhh (tropospheric ozone formation), PM (particulate matter), OFt (tropospheric ozone formation-eco), TA (terrestrial acidification), EF (freshwater eutrophication), ME (marine eutrophication), TE (terrestrial ecotoxicity), ECF (freshwater ecotoxicity), MEc (marine ecotoxicity), HCT (human toxicity-cancer), HNCT (human toxicity-non cancer), LU (land use), MRS (mineral resources), FRS (fossil resources), WU (water use)

- Comparison with ASs

Figure 3.6 illustrates the results of the different alternative scenarios examined in the analysis.

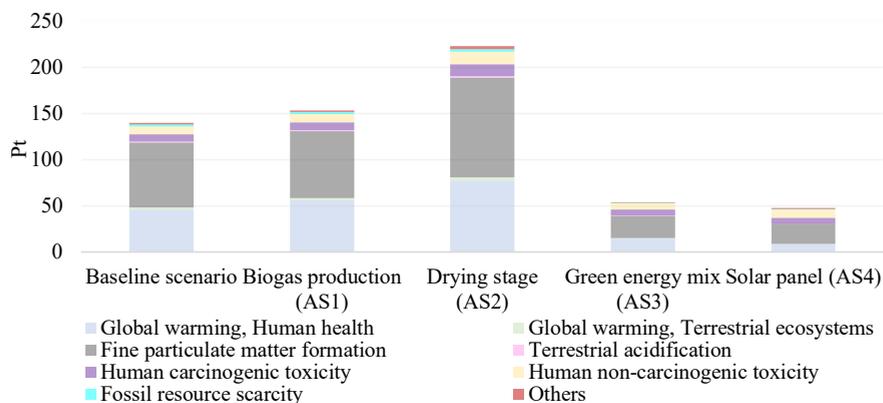


Fig. 3.6. Comparison with the ASs considering FU1. Note that “others” include all the other indicators contributing < 1 % to the total impact. From approbation publication No. 4 [73].

Among the alternative scenarios assessed, AS2 records the highest environmental burden, totaling 222.89 Pt. This result is largely attributed to the energy-intensive drying stage introduced to preserve biomass, which alone accounts for 37 % of the total impact. The integration of drying into the biorefinery process emerges as a critical design decision, requiring a careful evaluation of its necessity and the identification of more energy-efficient technological solutions if deemed essential. By contrast, scenarios that involve a transition to alternative electricity sources demonstrate considerable improvements in environmental performance. AS3, which incorporates a REC mix, achieves a footprint of 53.97 Pt, while AS4, based on solar energy integration, further reduces the impact to 47.48 Pt. These scenarios significantly outperform the baseline design reliant on Estonia’s conventional grid, cutting the overall impact by 61 % and 66 %, respectively. Comparing AS1 (biogas valorization of residues) with the baseline system highlights that the use of residues as fertilizer remains the more environmentally favorable end-of-life option. Fertilizer application results in a negative impact score of –8.82 Pt, indicating an environmental benefit, while biogas generation reaches a positive 4.30 Pt. This difference stems from the greater technological requirements and associated impacts of the biogas system. In both cases, a system expansion approach was adopted, assuming that fertilizer and electricity produced from *F. lumbricalis* residues displace conventional market equivalents. However, the simplicity of fertilizer application and the absence of additional infrastructure render it a more sustainable choice in the current biorefinery configuration.

- Comparison with alternative designs (SPE and TLE)

This section compares the environmental performance of the CB with the two alternative biorefinery configurations, SPE and TLE, using FU2, which is based on the quantity of process

output. The results, summarized in Fig. 3.7, highlight the differences across the three designs. Among the assessed configurations, the SPE model demonstrates the highest environmental impact, reaching 144.60 Pt. While the CB scenario provides a modest reduction of approximately 4 % in total impact compared to SPE, its primary advantage lies in the improved efficiency of biomass utilization. Through a cascading extraction approach, the CB system achieves equivalent product yields using only 1 ton of biomass, whereas SPE requires 3 tons to deliver the same outputs. In contrast, the TLE scenario exhibits the lowest environmental impact at 78.39 Pt, suggesting that a multi-line extraction approach could offer a more sustainable alternative. However, TLE does not achieve the same total product yield as CB. To enable fair comparison under FU2, additional conventional market products were integrated into the system boundary to compensate for the lower yield in TLE. This approach not only ensures methodological consistency but also reflects the growing market potential for macroalgae-derived compounds in the pharmaceutical, cosmetic, and food sectors.

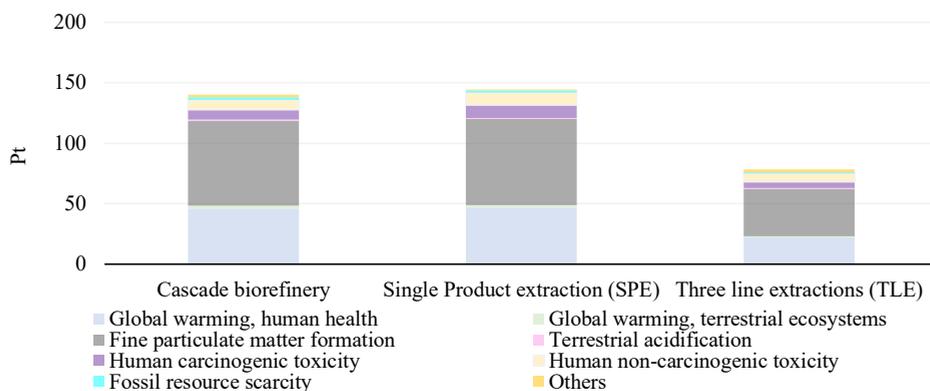


Fig. 3.7. Comparison between the CB system and the SPE and TLE referring to FU2. Note that “others” include all the other indicators contributing < 1 % to the total impact. From approbation publication No. 4 [73].

- Sensitivity analysis

A Monte Carlo analysis was performed to evaluate the sensitivity of environmental performance to fluctuations in energy consumption during the extraction phase. This simulation implements 10,000 iterations with a $\pm 20\%$ variation in energy use. The results, illustrated in Fig. 3.8, provide a comprehensive comparison across all biorefinery scenarios within a unified analytical framework.

The environmental impact outcomes ranged from a minimum of 19.65 Pt to a maximum of 239.45 Pt. The SPE configuration exhibited the broadest variation, with values spanning from 36.37 Pt to 239.48 Pt, while TLE showed a narrower range between 19.65 Pt and 129.88 Pt. Notably, the CB scenario demonstrated significant overlap with SPE, consistent with trends previously discussed in Fig. 3.12. An important finding emerged within the shared impact range of 47.64 Pt to 143.64 Pt, where all three scenarios intersected, accounting for approximately 17 % of the total simulation dataset. This suggests that in 83 % of simulations, the TLE configuration outperformed both the SPE and CB in terms of environmental performance.

These results underscore the potential of a three-line extraction biorefinery as a more sustainable alternative under varying energy consumption conditions.

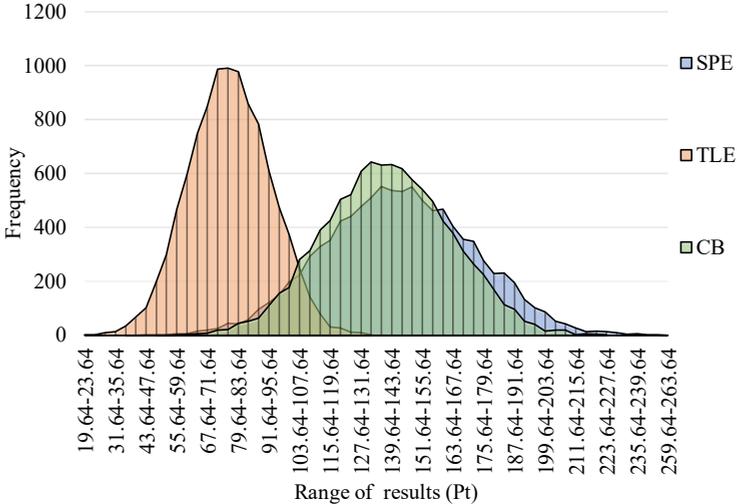


Fig. 3.8. Monte Carlo analysis for the comparison between CB, SPE, and TLE. From approbation publication No. 4 [73].

3.2. Economic results

Economic analysis results

- Operational costs

Figure 3.9 presents a comparative analysis of the operating costs associated with the five biorefinery designs.

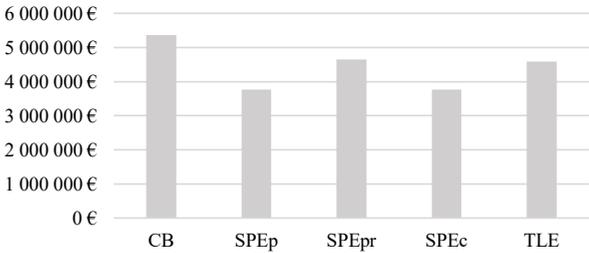


Fig. 3.9. Operative costs for CB, SPEp, SPEpr, SPEc, and TLE. These values are reported for 1 year.

The differences in operational expenditures among the various production scenarios are relatively limited. As expected, the CB scenario exhibits the highest operating cost, totaling 5,354,337 €/year. This is primarily attributed to the system's complexity and its ability to simultaneously generate multiple high-value end products, necessitating a more extensive and resource-intensive processing infrastructure. Among the single-product extraction

configurations, SPEp (3,766,787 €/year) and SPEc (3,771,810 €/year) report the lowest operational expenditures, with nearly identical cost structures. In contrast, SPEpr (4,642,929 €/year) and TLE (4,592,366 €/year) fall within an intermediate range, reflecting marginally higher operational demands than the more cost-efficient single-extraction alternatives, yet still remaining below the CB system. Figure 3.10 presents a detailed cost breakdown of the CB configuration, which is of particular relevance as it not only represents the most expensive scenario but also constitutes the core design examined in this Thesis.

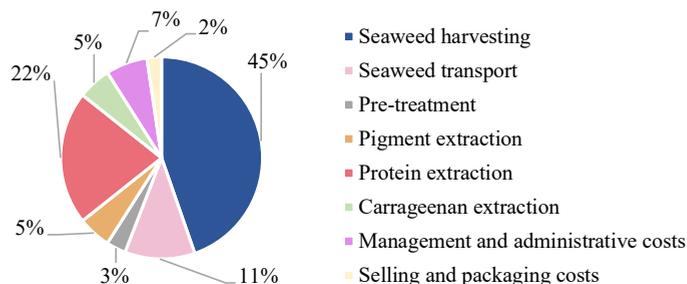


Fig. 3.10. Operative costs for the CB design. These values are reported for 1 year.

The cost allocation provides critical insight into the main economic drivers of the CB, helping to identify potential areas for process optimization. Notably, the most significant cost component is associated with the *F. lumbricalis* harvesting phase, which accounts for 2,391,458 €/year, approximately 45 % of the total operating costs. Of this, 90 % is attributed to diesel consumption for extraction and transportation. The second most costly phase is protein extraction, which amounts to 1,143,930 €, driven predominantly by the high cost of enzymes (e.g., alcalase) used during the hydrolysis process. Seaweed transport constitutes the third-largest expense, totaling 601,568 €, once again heavily influenced by fuel consumption. These results indicate that fuel dependency and enzyme procurement are the principal economic constraints within the CB system, underscoring the importance of improving fuel efficiency and investigating alternative or lower-cost enzymatic solutions to enhance the system's overall economic sustainability.

- Investments

Figure 3.11 illustrates the investment costs associated with the various biorefinery configurations. The TLE design presents the highest capital requirement, amounting to 3,459,086 €, due to the need to operate three separate extraction lines concurrently. This configuration entails a greater number of processing units and expanded infrastructure, thereby elevating the overall investment. The CB system follows, with an investment cost of 2,058,558 €, reflecting the technological complexity inherent in the cascade biorefinery setup. As anticipated, the SPE configurations require the lowest upfront investments, as their focus on single-product extraction minimizes the need for extensive machinery and infrastructure.

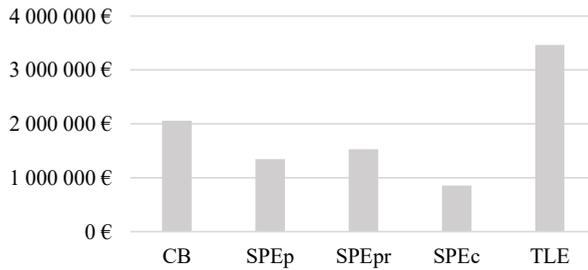


Fig. 3.11. Investment costs for CB, SPEp, SPEpr, SPEc, and TLE.

Figure 3.12 offers a detailed breakdown of the investment costs for the CB configuration, which also serves as a representative model for understanding the cost structure of the other designs.

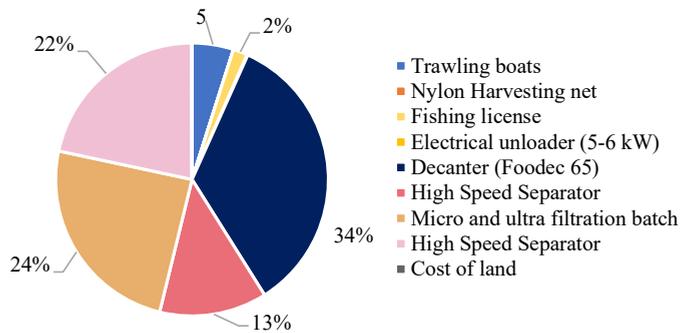


Fig. 3.12. Breakdown of the investment cost for the CB biorefinery design.

The Foodec 65 decanters constitute the largest share of the investment, accounting for 34 % of the total cost. These units are essential for the efficient separation of biomass and liquid fractions, a critical step in the production of high-quality pigments, proteins, and carrageenan. The micro- and ultrafiltration units follow, comprising 24 % of the total investment, as they play a central role in ensuring the purity of extracted compounds. The PurePulp 750 and Clara 200 high-flow high-speed separators contribute 22 % and 13 %, respectively, reflecting their importance in refining and concentrating the bioproducts. Additionally, smaller-scale investments include a trawling vessel, nylon collection nets, annual harvesting licenses, an electric unloader (featuring a 5–6 kW hydraulic pump), and land acquisition. Although these components represent a relatively minor portion of the overall investment, they are essential for establishing a fully operational and efficient *F. lumbricalis* biorefinery.

- Sales scenarios

An analysis of revenue generation under variable market conditions, namely the WCS and BCS, was conducted to evaluate the financial resilience of the proposed biorefinery configurations. The results, presented in Fig. 3.13, depict the fluctuations in revenue across different economic scenarios. These findings, focused exclusively on revenue from product sales, provide a preliminary insight into the economic potential of the various biorefinery

systems. As anticipated, the CB and SPEp configurations, both of which prioritize pigment extraction, demonstrate the highest revenue outcomes. In contrast, SPEpr, centered on protein recovery, yields substantially lower revenues, thereby increasing the risk of economic non-viability under adverse market conditions. While this analysis does not constitute a full economic evaluation, it establishes a foundational reference point for subsequent financial assessments. By identifying the influence of product pricing and biomass availability on overall revenue, this preliminary step enhances the robustness and credibility of the broader techno-economic analysis.

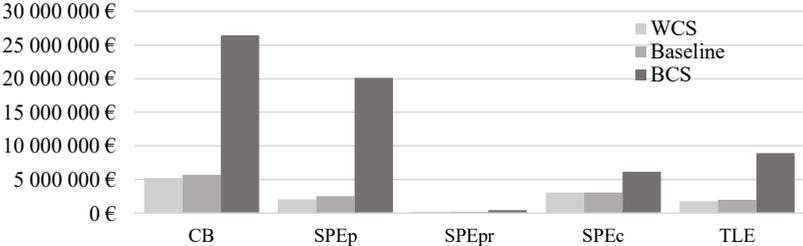


Fig. 3.13. Comparative analysis of the sales scenarios, including WCS and BCS.

- Environmental monetarization results

Figure 3.13 presents a comparative analysis of the environmental costs associated with the different biorefinery configurations. Consistent with the initial LCA results, the CB incurred the highest environmental cost, amounting to 707,731 €, followed by the TLE (441,437 €), SPEc (421,116 €), SPEpr (304,595 €), and SPEp (202,964 €) scenarios. However, when normalized to the total product output, the interpretation shifts: replicating the product yield of the CB would require combining the outputs from SPEp, SPEpr, and SPEc, resulting in a cumulative environmental cost of 928,676 €. This outcome suggests that the consolidated single-product extraction designs are more environmentally costly than the CB configuration. A more detailed analysis of the cost distribution reveals that GWP accounts for the largest share of environmental costs (63 %), followed by PM at 13 %, and FRS at 12 %. Notably, this distribution contrasts with the original LCA results, where the PM was the dominant impact category, and FRS had a relatively minor influence. This divergence highlights the critical role of the monetarization factors, underscoring how their application can significantly alter the interpretation and prioritization of environmental impacts within a cost-based framework.

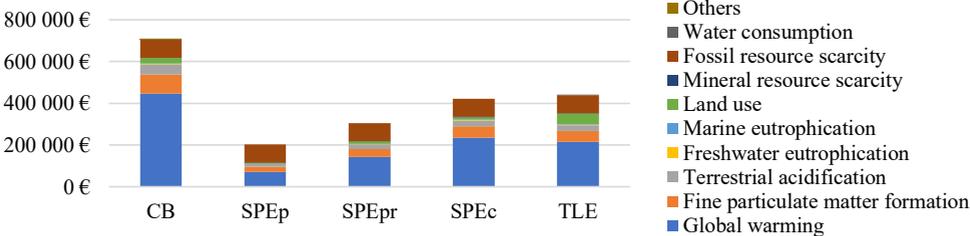


Fig. 3.13. Comparative analysis of the environmental externalities. Note that others include the sum of all the ReCiPe2016 indicators with an impact lower than 1 €.

Comparative economic assessments

Table 3.4 presents a comprehensive economic assessment of various biorefinery configurations over a 10-year period. Under the WCS, all scenarios yield negative ROI values, indicating persistent financial losses. SPEpr and TLE are the least viable, exhibiting extreme ROIs of $-1,934\%$ and $-1,262\%$, respectively. These findings are reinforced by NPV calculations, where SPEpr reports the most severe loss at $-31,904,995\text{ €}$. Across all configurations, IRR remains incalculable, further confirming their inability to generate financial returns. Negative PI values also reflect this trend, with SPEpr again ranking lowest at -15.50 , cementing its status as the least economically feasible option.

In the baseline scenario, the CB emerges as the only design achieving a positive ROI of 41% , suggesting moderate profitability. However, its NPV remains negative, indicating that recouping initial investments may still be challenging. The remaining designs continue to demonstrate negative NPVs and PIs, with SPEpr again performing worst. While CB shows relatively better performance, its financial sustainability under baseline conditions remains marginal and insufficient for confident industrial-scale implementation. Conversely, in the BCS, both CB and SPEp show strong financial viability. CB achieves an ROI of $5,147\%$ and an NPV of $82,437,798\text{ €}$, while SPEp follows closely with an ROI of $4,111\%$ and an NPV of $65,710,001\text{ €}$. Both scenarios also report high IRRs (559% and 447% , respectively) and positive PI values (40.05 and 31.92), indicating substantial profitability under favorable market conditions. In contrast, SPEpr, SPEc, and TLE remain unprofitable, with SPEpr again incurring the highest losses (NPV of $-61,516,773\text{ €}$).

Table 3.4

Comparative economic analysis of the different scenarios					
	CB	SPEp	SPEpr	SPEc	TLE
<i>Worst case scenario (WCS)</i>					
ROI	-154%	-802%	$-1,934\%$	-389%	$-1,262\%$
NPV	$-3,168,612\text{€}$	$-13,623,485\text{ €}$	$-31,904,995\text{ €}$	$-6,964,791\text{ €}$	$-21,060,533\text{ €}$
IRR	Not calculable	Not calculable	Not calculable	Not calculable	Not calculable
PI	-1.54	-6.62	-15.50	-3.38	-10.23
<i>Baseline scenario</i>					
ROI	41%	-596%	$-1,934\%$	-389%	$-1,194\%$
NPV	$-17,318\text{ €}$	$-10,306,897\text{ €}$	$-31,904,995\text{ €}$	$-6,964,791\text{ €}$	$-19,954,451\text{ €}$
IRR	-0.17%	Not calculable	Not calculable	Not calculable	Not calculable
PI	-0.01	-5.01	-15.50	-3.38	-9.69
<i>Best case scenario (BCS)</i>					
ROI	$5,147\%$	$4,111\%$	$-3,768\%$	-679%	-209%
NPV	$82,437,798\text{ €}$	$65,710,001\text{ €}$	$-61,516,773\text{ €}$	$-11,636,363\text{ €}$	$-4,055,130\text{ €}$
IRR	559%	447%	Not calculable	Not calculable	Not calculable
PI	40.05	31.92	-29.88	-5.65	-1.97

Overall, the CB configuration stands out as the most robust and economically promising design, demonstrating resilience in the baseline scenario and strong profitability in the BCS, while maintaining comparatively lower losses in the WCS. These findings emphasize the critical role of pigment extraction in determining the financial sustainability of an *F. lumbricalis* biorefinery. Systems focused on protein or carrageenan extraction or lacking an integrated cascade approach consistently underperform and are economically unsustainable. Across all

designs, raw material extraction and transport represent the most significant cost drivers. The heavy reliance on diesel fuel for the trawling boat contributes substantially to operational expenditures, a concern exacerbated by volatile energy prices in Europe, influenced by geopolitical tensions and the transition to fossil-free energy sources [110]. The CB incurs the highest operating costs (5,354,337 €/year) due to its multi-product extraction approach, which requires complex processing infrastructure. Harvesting operations alone account for 2,391,458 €/year, with 90 % of this cost attributed to fuel consumption. Protein extraction is the second-largest expense (1,143,930 €), primarily due to the high cost of enzymes like alcalase. Seaweed transport ranks third (601,568 €), again largely driven by fuel use. Investment costs follow a similar trend, with the Foodec 65 decanter representing the largest expenditure, followed by advanced filtration systems. These components are essential for biomass separation and high-quality product recovery, forming the technological backbone of the CB. The financial performance of these designs is highly sensitive to market dynamics, particularly pigment pricing and biomass processing volumes. The profitability of CB under the BCS scenario, where pigment prices reach 500,000 €/ton, contrasts sharply with the financial fragility observed when prices drop to 100,000 €/ton. This highlights the need for robust market forecasting, flexible pricing strategies, and risk management to ensure long-term viability, especially considering that pigment sales constitute the principal revenue stream.

3.3. Social results

Results of the IPA approach

Using the IPA methodology, the primary objective is to develop a social hotspot map for the WH and OFC value chains associated with the production of *F. lumbricalis*. These reference systems are thoroughly described in Sections 2.1 and 2.4. In this summary, only the full results for the WH scenario are disclosed, as they represent the actual case study. The OFC configuration is included as a benchmark for comparative purposes and is fully detailed in the full manuscript.

- WH results

Table 3.5 presents the results for the sub-categories in the WH scenario, using a color-coded scale ranging from red (indicating the highest potential social risk) to green (representing the lowest potential social risk).

Table 3.5

Sub-category results 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 labor	0.01274	0.00355	0.00197	0.00519	0.0234	mrheq
Forced labor	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 labor	0.00982	0.00241	0.00201	0.00421	0.0185	mrheq
Social benefits	0.00711	0.00190	0.00116	0.00352	0.0137	mrheq
Labor laws/convns.	0.00387	0.00119	0.00125	0.00152	0.0078	mrheq

Impact category	Seaweed harvesting	Maintenance of boat	Transport to the harbor	Boat unloading	Total	Unit
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

The analysis highlights harvesting operations as the stage with the highest potential social risk, closely followed by boat unloading procedures. Among the evaluated indicators, *injuries & fatalities* exhibit the highest potential risk (0.0482 mrheq), raising concerns about occupational safety in this sector. Additionally, *forced labor* (0.0419 mrheq) and *discrimination* (0.0361 mrheq) also emerge as significant risks that warrant further attention. To support a more comprehensive understanding, Fig. 3.14 presents the normalized and weighted results grouped into broader damage categories. This categorization enables a deeper interpretation of the social implications tied to the WH scenario. Seaweed harvesting stands out as the stage with the highest overall social risk, with a total impact of 226.85 S-Pt. The most prominent individual indicators are *access to electricity* (22.36 S-Pt), *labor law/conventions* (20.51 S-Pt), and *occupational toxicity & hazards* (18.50 S-Pt). In terms of damage categories, *labor rights & decent work* (163.45 S-Pt), *community* (100.82 S-Pt), and *society* (92.05 S-Pt) are the most affected, underscoring the need for targeted improvements in the harvesting phase.

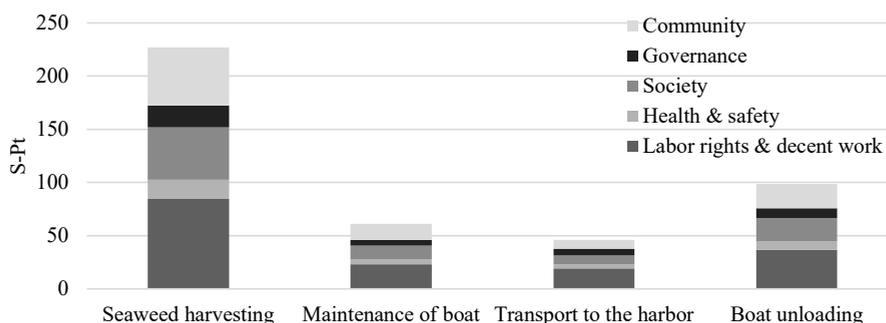


Fig. 3.14. Normalized and weighted results for the WH scenario. The results are provided in normalized social-points (S-Pt).

A notable finding in the WH scenario emerges from the SHDB analysis, which reveals that the highest impact indicator, *access to electricity*, does not primarily affect Estonia but rather impacts upstream supply chain countries such as the Ivory Coast and Ghana (see Fig. 3.15). Similarly, other indicators, such as *occupational toxicity & hazard*, identify China as one of the most affected regions. These results underscore the globally distributed nature of social risks within macroalgae value chains, highlighting that significant social impacts may originate far from the geographical boundaries of the system under study.



Fig. 3.15. Countries' hot spot analysis results for the normalized *access to electricity* indicator.

- Comparison results

Figure 3.16 presents a comparative analysis of the two scenarios, illustrating that OFC exhibits a significantly higher potential social impact than WH. The total impact score for OFC reaches 719.51 S-Pt, whereas WH registers a lower score of 432.85 S-Pt. This discrepancy indicates that OFC is associated with greater social risks across key categories, including labor rights, community well-being, governance, and health and safety. To enhance the robustness of these findings, a Monte Carlo simulation was performed to account for variability in key input parameters. The simulation, based on 5,000 iterations, provides a probabilistic distribution of potential social impact outcomes. The results, also depicted in Fig. 3.17, reveal distinct value ranges for each scenario: WH impacts fluctuate between 411.5 and 454.5 S-Pt, while OFC shows a broader spread from 678.1 S-Pt to 753.3 S-Pt. Notably, the absence of any overlap between the two ranges confirms a consistent trend favoring WH in terms of lower social impacts.

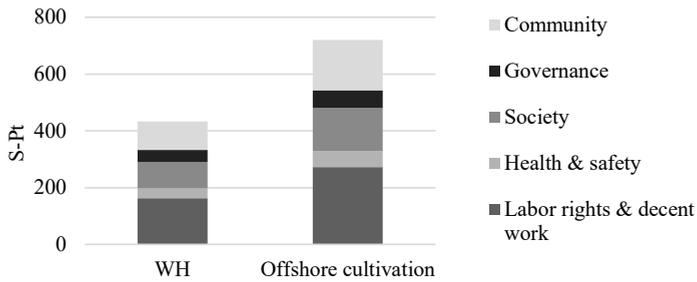


Fig. 3.16. Comparison results for the WH and OFC scenarios.

These results substantiate the conclusion that, under the current assumptions and data framework, OFC does not offer a social sustainability advantage over WH. This emphasizes the importance of prioritizing WH-based practices while concurrently exploring strategies to mitigate the social risks inherent in OFC systems.

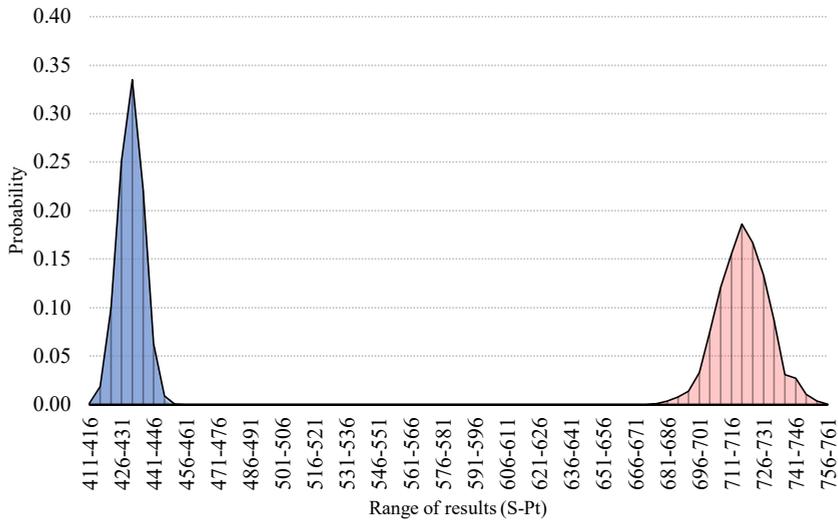


Fig. 3.17. Monte Carlo simulation results for the WH and OFC scenarios. The red chart is OFC, and the blue one is the WH.

Results of the RSA approach

The RSA approach offers a more focused S-LCA by integrating stakeholder-specific insights obtained through questionnaires administered to a panel of eight experts. These questionnaires were developed to evaluate the social risks associated with both upstream operations (i.e., macroalgae harvesting and cultivation) and downstream processes (i.e., macroalgae processing), in alignment with the stakeholder groups and social indicators identified in Table 2.8.

- Social risk results for harvesting & cultivation

The results for the harvesting and cultivation phase are presented in Table 3.6. The analysis identifies critical concerns in certain areas, most notably regarding the *health and safety* of

workers, which received an average score of -0.43 . This negative rating signals a moderate level of social risk, suggesting that worker well-being is insufficiently protected and warrants immediate attention. Conversely, *economic development* within local communities was identified as a strength, with a consistently high score of 2.00 . This very low-risk rating reflects an expert consensus on the significant economic benefits generated by macroalgae harvesting for surrounding regions. Other aspects reveal moderate concerns. *Working hours* received an average score of 0.14 , pointing to inconsistencies that may require policy standardization. Similarly, *safe and healthy living conditions* for local communities scored 0.00 , reflecting high variability across different contexts, indicating that while some communities benefit from these operations, others experience adverse conditions that must be addressed. The indicator *consumers' health and safety* received a moderately positive average score of 0.75 , denoting generally low risk but suggesting room for further improvement. *Transparency* achieved a score of 0.67 , indicating low to moderate risk; however, the presence of negative responses suggests that communication and information-sharing practices could be strengthened. The stakeholder group representing the value chain recorded the highest number of null responses, pointing to a gap in expertise that may hinder a fully comprehensive evaluation. *Fair competition* was rated at 0.67 , reflecting a low overall risk, though occasional high-risk responses underscore the need to address imbalances in market access and fairness. Finally, *promoting social responsibility* and *wealth distribution* each received scores of 0.33 , indicating moderate risks and highlighting the importance of reinforcing ethical practices and improving economic equity throughout the supply chain.

Table 3.6

Analysis of the social risk for the macroalgae harvesting & cultivation operations

Indicators	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	Average
<i>Workers</i>									
Health and safety	0	2	-2	2	1	-2	-2	-2	-0.43
Working hours	0	2	2	2	-1	-2	-1	-1	0.14
Social benefits/social security	0	2	1	2	0	0	2	0	1.75
<i>Local community</i>									
Safe and healthy living conditions	0	2	-1	2	-2	-2	-1	2	0.00
Local economic development	2	2	2	2	2	2	2	2	2.00
<i>Consumers</i>									
Health and safety	0	0	-1	2	0	1	0	1	0.75
Transparency	0	1	2	2	-1	-2	0	2	0.67
<i>Value chain</i>									
Fair competition	0	0	-1	2	0	0	1	0	0.67
Promoting social responsibility	0	1	-1	1	0	0	0	0	0.33
Wealth distribution	0	-1	1	1	0	0	0	0	0.33

- Macroalgae processing social risk

Table 3.7 presents the results for the seaweed processing stage, highlighting key social indicators across various stakeholder categories. Within the *workers* category, the *health and safety* indicator received an average score of 0.14 , indicating a moderate level of risk. While certain areas demonstrate satisfactory conditions, there remain concerns that warrant targeted

interventions to enhance worker well-being. Notably, this score is higher than that observed in the macroalgae harvesting phase, suggesting that downstream processing operations pose a comparatively lower occupational hazard. The *working hours* indicator scored an average of 0.29, similarly reflecting moderate risks, with some inconsistencies in scheduling practices that may necessitate standardization across the sector. In contrast, the *social benefits/social security* indicator achieved a high average score of 1.75, signifying low risk and suggesting that workers generally enjoy reliable access to social support systems and welfare provisions. In the *local community* category, the *safe and healthy living conditions* indicator reached an average score of 0.83, pointing to low-risk and broadly acceptable living standards in areas surrounding processing operations. Nonetheless, some variability indicates that improvements may still be needed in specific contexts. The *local economic development* indicator once again scored consistently high at 2.00, reflecting very low risk and highlighting the substantial positive economic contributions of the seaweed processing industry to local communities. For *consumers*, the *health and safety* indicator recorded a positive average score of 0.75, confirming a low risk in this domain. However, the presence of at least one negative response underscores the importance of continuous efforts to uphold and enhance safety standards. The *transparency* indicator, with an average score of 0.20, suggests a moderate risk. Negative feedback within this category indicates that transparency mechanisms should be strengthened to build greater consumer confidence and accountability within the sector. In the *value chain* category, the *fair competition* indicator received a strong positive score of 2.00, suggesting a well-functioning and equitable competitive environment with minimal risk. However, the *promoting social responsibility* indicator scored 0.00, indicating a neutral risk level. While some initiatives are in place, they are not yet widespread, pointing to opportunities for further development. The *wealth distribution* indicator received a negative average score of -0.67, highlighting a moderate to high level of risk. This outcome suggests persistent economic disparities and emphasizes the need for targeted strategies to ensure a more equitable distribution of economic benefits across the value chain.

Table 3.7

Analysis of the social risk for the macroalgae processing operations

Indicators	No.	Average							
	1	2	3	4	5	6	7	8	
<i>Workers</i>									
Health and safety	0	2	-1	2	1	-1	-1	-1	0.14
Working hours	0	2	-1	2	-1	-1	-1	2	0.29
Social benefits/social security	0	2	1	2	0	0	2	0	1.75
<i>Local community</i>									
Safe and healthy living conditions	0	2	-1	2	0	-1	2	1	0.83
Local economic development	2	2	2	2	2	2	2	2	2.00
<i>Consumers</i>									
Health and safety	0	0	-1	2	0	1	0	1	0.75
Transparency	0	1	-2	2	0	-2	0	2	0.20
<i>Value chain</i>									
Fair competition	0	0	0	2	0	0	2	0	2.00
Promoting social responsibility	0	1	-2	1	0	0	0	0	0.00
Wealth distribution	0	-1	-2	1	0	0	0	0	-0.67

- Take-home messages from the social survey

Based on the findings, experts consistently identified no social risk for the *local economic development* indicator, assigning it a score of +2 across both the harvesting & cultivation and processing phases. This positive outcome is attributed to improvements in local infrastructure, such as the expansion of services that support macroalgae-related operations, as well as the potential to attract tourism interest. Seaweed-related employment can also sustain local economic activity during off-seasons when harvesting is not feasible. In small, remote locations such as islands, jobs in the macroalgae sector may represent one of the few available employment opportunities, reinforcing its economic significance. A similar trend was observed for the *social benefits/social security* indicator, which received an average score of +1.75. However, only 50 % of the surveyed experts responded to this indicator, introducing a level of uncertainty. The seasonal nature of macroalgae harvesting raises concerns about potential disparities in social protections, as seasonal workers may not enjoy the same benefits as full-time employees, potentially resulting in inequities in worker rights. For the *fair competition* indicator, the processing phase was deemed free from social risk, whereas a low risk was identified in the biomass preparation stage. Moderate risks were observed in two key areas: *health and safety of workers* during harvesting and cultivation (-0.43) and *wealth distribution* during the processing phase (-0.67). Occupational risks in harvesting and cultivation primarily stem from offshore activities, where unpredictable weather conditions and machinery failures pose significant hazards. Moreover, these operations are concentrated in short time windows, requiring intense labor efforts that elevate the risk of workplace injuries. The physically demanding nature of the work also raises concerns about long-term health impacts, particularly musculoskeletal disorders. The introduction of electric loaders and other mechanized equipment could mitigate these risks by reducing the reliance on manual labor. In the processing phase, risks are primarily associated with exposure to cutting and milling machinery, which necessitates specialized training and safety protocols. Additionally, the use of chemicals during macroalgae processing reinforces the need for comprehensive protective measures and equipment. Regarding *wealth distribution*, findings suggest a potential imbalance in the allocation of financial gains from biorefinery operations, raising concerns that economic benefits may not be equitably shared across stakeholders in the value chain. For the *safe and healthy living conditions* indicator, macroalgae-related activities were generally perceived to pose lower risks than traditional aquaculture operations, such as fish or mussel farming, which can lead to nutrient accumulation, ecological disruption, and storm-related damage. However, intensive macroalgae harvesting using diesel-powered vessels introduces environmental risks, including the emission of oil and polycyclic aromatic hydrocarbons, which may negatively affect marine ecosystems and coastal communities. Additionally, the use of antifouling agents on boats may lead to the leaching of hazardous substances, causing long-term harm to local marine biodiversity. The *transparency* indicator raised concerns among respondents about misleading or unverified claims regarding the environmental benefits of macroalgae biomass. These claims are sometimes used in marketing without scientific validation, potentially resulting in consumer misinformation. To mitigate this risk, it is recommended that publicly

accessible, evidence-based composition analyses be made available to ensure accurate and transparent communication of macroalgae's properties and benefits.

A major challenge in conducting this S-LCA was data collection, an issue common to many S-LCA applications. International databases such as SHDB and PSILCA are not yet equipped to fully reflect the social dynamics of small-scale operations like the *F. lumbricalis* biorefinery, particularly within the local community context. To address this gap, a stakeholder engagement strategy was implemented using expert questionnaires. Despite a broad outreach effort, only eight out of more than 20 experts responded. While the sample size was limited, the responses provided valuable insights and marked a first step toward enhancing the social sustainability understanding of the macroalgae sector. One key limitation of the study was the lack of data related to "other value chain actors". The high proportion of null responses for this stakeholder group highlights a critical area for improvement in future assessments. Indicators such as *fair competition*, *promotion of social responsibility*, and *wealth distribution* remain underexplored, and future research should place greater emphasis on engaging these actors to fill this knowledge gap. A more engaged expert community is essential to improve the robustness and accuracy of social sustainability evaluations in this sector.

3.4. Final sustainability index

TOPSIS results

In the first step of the TOPSIS approach, each selected indicator across the three sustainability dimensions, environmental, economic, and social, was classified according to whether it should be maximized or minimized in alignment with an ideal sustainability scenario. This classification is essential to ensure a coherent and systematic assessment of sustainability performance across all criteria. This classification process, along with the initial weights assigned to each criterion, is comprehensively summarized in Table 3.8.

The normalization matrix standardizes the values of each sustainability indicator, ensuring comparability across differing units and measurement scales. This step is a fundamental component of the TOPSIS methodology, as it transforms the raw data into a dimensionless format, enabling consistent and equitable assessment of sustainability performance across the three biorefinery scenarios: CB, SPE, and TLE. The normalized values offer a harmonized representation of each criterion, ensuring that no single indicator disproportionately influences the overall evaluation. Following normalization, a weighted normalization matrix was constructed to integrate the relative importance of each criterion. Subsequently, the Euclidean distances to both the ideal and anti-ideal solutions were calculated, facilitating the identification of the most sustainable biorefinery configuration among the assessed alternatives.

Table 3.11

Indicators and decision criteria. MIN and MAX indicate if a criterion has been minimized or maximized, respectively, in comparison to an ideal scenario

Dimension	Indicator	Unit	Type	MIN/MAX	Weights
Environmental	Global warming potential	kg CO ₂ eq.	Quantitative	MIN	0.083
	Fine particulate matter formation	kg PM _{2.5}	Quantitative	MIN	0.083
	Human carcinogenic and non-carcinogenic toxicity	kg 1.4-DCB	Quantitative	MIN	0.083
	Water consumption	m ³	Quantitative	MIN	0.083
Economic	Return on investment	%	Quantitative	MAX	0.083
	Net present value	EUR	Quantitative	MAX	0.083
	Internal rate of return	%	Quantitative	MAX	0.083
	Profitability index	-	Quantitative	MAX	0.083
Social	Health & safety of the worker	-	Semi-quantitative	MAX	0.083
	Working hours	-	Semi-quantitative	MAX	0.083
	Local economy development	-	Semi-quantitative	MAX	0.083
	Wealth distribution	-	Semi-quantitative	MAX	0.083

Figure 3.8 visually depicts the results, showcasing the comparative sustainability performance of CB, SPE, and TLE. Among the evaluated biorefinery configurations, the CB design emerged as the most sustainable option, attaining a closeness coefficient (P_i) of 0.776. This value places it nearest to the ideal sustainability scenario ($P_i = 1$), reflecting its balanced performance across environmental, economic, and social dimensions. The TLE design followed with a P_i value of 0.492, indicating a moderate sustainability profile. In contrast, the SPE configuration yielded the lowest P_i value (0.229), underscoring its limitations in achieving a holistic sustainability outcome and reinforcing the challenges associated with mono-product valorization strategies.

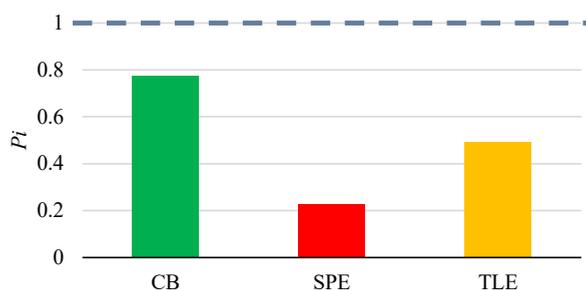


Fig. 3.8. Results of the LCSA following the TOPSIS approach. The blue line represents the ideal scenario benchmark.

Sensitivity analysis

To enhance the robustness of the analysis, a sensitivity assessment was performed by systematically varying the weight assigned to each of the three sustainability pillars: environmental, economic, and social. This evaluation aimed to determine the extent to which changes in weight distribution influence the ranking of the biorefinery configurations. The results of this analysis are presented in Fig. 3.9.

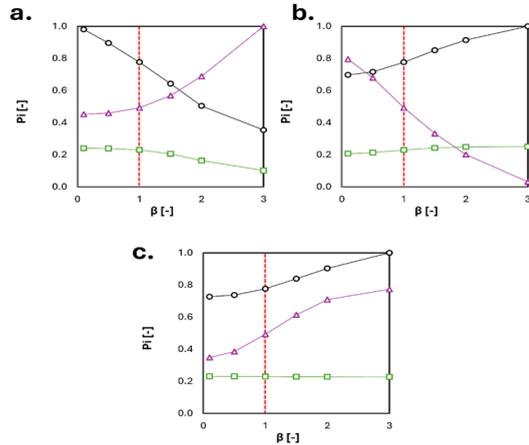


Fig. 3.9. Results of the sensitivity analysis for weights to (a) environmental, (b) economic, and (c) social criteria. Closeness coefficient (P_i) as a function of the variation ratio (β).

The black line represents the CB, the violet line SPE, and the green line TLE. The red dashed line indicates the results of the LCSA before the sensitivity analysis.

Table 3.10 summarizes the probability distribution of rankings for each scenario based on the sensitivity analysis simulations.

Table 3.10

Probability ranking of the different design approaches			
Probability ranking			
Design	Best scenario	Mid scenario	Worst scenario
CB	80 %	20 %	0 %
SPE	0 %	47 %	53 %
TLE	20 %	33 %	47 %

The CB consistently emerged as the most sustainable option, ranking first in 80 % of the 15 simulated scenarios. The findings indicate that the environmental dimension exerts a substantial influence on the final ranking. In two cases where environmental sustainability received the highest weighting, the TLE configuration surpassed CB, highlighting the importance of prioritizing environmental considerations in the future optimization of *F. lumbricalis* biorefineries. Economically, CB demonstrated superior performance due to its capacity to produce multiple high-value products, which enhances market resilience and overall profitability. In contrast, TLE faced limitations arising from the initial fractionation of biomass, which constrains product yields and diminishes economic viability. Notably, in simulations

where economic performance was given the greatest importance, TLE ranked below the SPE system, further illustrating its financial drawbacks. In terms of social sustainability, no rank inversions were observed. This stability may be attributed to the semi-quantitative nature of the input values, which limits the granularity of differentiation among the scenarios with respect to social performance.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

This Doctoral Thesis introduced an innovative CB concept for the red macroalga *F. lumbricalis* within the Baltic Sea Region, supported by a comprehensive LCSA. By integrating LCA, LCC, and S-LCA, the study delivers a multidimensional evaluation of sustainability for three distinct biorefinery configurations: CB, SPE, and TLE. Key findings are summarized. State-of-the-art review

The literature review highlighted that macroalgae biorefinery research remains largely at the laboratory scale, with a predominant focus on brown macroalgae. Red macroalgae, including *F. lumbricalis*, are significantly underrepresented, particularly in LCA and S-LCA studies. This research addresses a critical knowledge gap by providing a comprehensive analysis of red macroalgae valorization pathways.

- Technological development of the cascade biorefinery

A complete CB model was developed, integrating pigment, protein, and carrageenan extraction. The system maximizes biomass utilization and includes optional end-of-life treatment of residual biomass via fertilizer production or biogas generation. Compared to conventional SPE and TLE systems, the CB demonstrated markedly improved resource efficiency and product yield from a fixed biomass input.

- Critical role of process design

A comparative evaluation of three pigment extraction methods, EAE, UAE, and water extraction, highlighted EAE as the most sustainable due to its superior yield, solvent reuse, and balanced environmental and economic performance. The UAE was limited by high energy use, while water extraction performed poorly due to low efficiency. The results emphasize the need to optimize both yield and energy demand in future biorefinery process design.

- Environmental analysis of upstream processes

Three macroalgae sourcing strategies, WH, OFC, and ONC, were compared. ONC exhibited the highest environmental burden (56.21 mPt), followed by OFC (22.76 mPt) and WH (11.10 mPt). Alternative scenarios revealed considerable potential for improvement, particularly in ONC, where replacing LED lighting with natural sunlight reduced impacts by 78.25 %. In the WH scenario, substituting the antifouling agent resulted in a 28.02 % impact reduction, achieving the lowest total footprint (7.99 mPt).

- Environmental analysis of the full biorefinery system

For the LCA of the full CB process under FU1 (1 ton DW biomass), the total environmental burden was 140.08 Pt (with fertilizer application) and 153.22 Pt (with biogas generation). Carrageenan extraction represented the most impactful stage, driven by high energy consumption. The use of residual biomass as fertilizer proved more sustainable, offering an avoided impact of -8.82 Pt. Under FU2 (based on product yield), the TLE scenario exhibited the lowest impact (78.39 Pt), though it delivered reduced product output. The CB remained the most efficient model in terms of biomass valorization.

- Economic sustainability

The CB emerged as the most economically promising design due to its ability to diversify outputs and capture high-value products. However, its financial viability is highly sensitive to market conditions, especially pigment prices. The CB also incurs the highest operating and capital costs, suggesting a need for process optimization and potential financial support mechanisms. SPE and TLE configurations were economically unviable under most scenarios due to limited product yields and reduced system efficiency.

- Social analysis – IPA approach (upstream)

The S-LCA using the IPA revealed that WH carries lower social risks than OFC, particularly in categories such as labor rights, health and safety, and community well-being. Technological improvements and better governance would be essential to enhance the social acceptability of OFC systems. The analysis demonstrated the global distribution of social impacts, often manifesting in distant supply chain countries, emphasizing the importance of adopting a life cycle perspective in social assessments.

- Social analysis – RSA approach (full biorefinery)

The RSA approach to the biorefinery process identified positive contributions to local economic development and employment, particularly in small or remote communities. However, risks related to occupational safety and unequal wealth distribution along the supply chain remain critical challenges. Limited stakeholder engagement and data availability, particularly concerning value chain actors, highlight the need for deeper involvement and broader data collection in future S-LCA studies.

- Sustainability index

The integration of environmental, economic, and social indicators using the TOPSIS method confirmed the CB as the most sustainable configuration. The CB achieved the highest overall sustainability score ($P_i = 0.776$), followed by TLE ($P_i = 0.492$) and SPE ($P_i = 0.229$). Sensitivity analyses confirmed the robustness of the CB's ranking, although environmental prioritization occasionally favored the TLE system.

Recommendations

- Pilot and scale-Up

Translating the CB concept from theoretical modeling and laboratory-scale testing to industrial-scale deployment is a crucial next step. Pilot-scale initiatives should aim to validate extraction yields, equipment functionality, and system scalability under real operating conditions. These pilots will also inform logistics planning, site-specific operational parameters, and workforce requirements. Effective collaboration among academia, technology providers, and industry stakeholders will be essential to drive scale-up and de-risk investment.

- Energy optimization

Both LCA and LCC results identified energy consumption, particularly in drying and heating operations, as a primary environmental and economic hotspot. Investments in energy-efficient technologies, such as low-temperature or vacuum-assisted drying systems, waste heat recovery, and optimized heat exchangers, can substantially reduce impacts. Integrating

renewable energy sources, such as solar photovoltaic systems or bio-based electricity, is also strongly recommended to align with decarbonization goals and improve system sustainability.

- Market strategy development

Economic sustainability depends heavily on the ability to access and grow high-value markets. Improving product quality, safety, and regulatory compliance is essential for entering the food, cosmetic, pharmaceutical, and agricultural sectors. Expanding the product portfolio (e.g., nutraceuticals, bio-stimulants, or biodegradable materials) can reduce market risk and increase resilience. The co-development of standards, labeling schemes, and third-party certifications will support consumer trust and facilitate broader market adoption.

- Improved data for S-LCA

The current lack of high-quality, localized social data presents a major limitation for S-LCA in the macroalgae sector. Future research should focus on collecting site-specific, community-level, and gender-sensitive data to improve the accuracy and representativeness of social impact assessments. Increased stakeholder engagement, through interviews, participatory design workshops, and citizen science initiatives, will enhance both data quality and the inclusiveness of sustainability planning.

- Policy support and incentives

Enabling policy frameworks are critical to unlocking investment and accelerating development in the macroalgae biorefinery sector. Public institutions should implement targeted funding instruments, tax incentives, and streamlined permitting procedures for macroalgae-based innovations. Developing clear regulatory guidelines for novel macroalgae products (e.g., food-grade or pharmaceutical applications) will help reduce uncertainty and catalyze private-sector engagement.

- Framework extension to other macroalgae

The LCSA framework established in this Thesis is designed to be replicable and adaptable. Future applications should explore its transferability to other macroalgae species, biomass compositions, cultivation systems, and geographical settings. Comparative assessments can yield best practices and inform the development of region-specific biorefinery models for broader uptake across the blue bioeconomy.

- Integration with other circular economy sectors

Sustainability performance can be enhanced through circular synergies with adjacent sectors, such as aquaculture, agriculture, or wastewater treatment. For instance, co-locating biorefineries with aquaculture facilities may enable nutrient recycling, energy co-generation, or by-product valorization, thereby lowering costs and environmental burdens. Such cross-sector integration aligns with circular economy principles and can further strengthen business models.

- Capacity building and education

The macroalgae sector requires a skilled workforce to support its growth and innovation. Investments in vocational training, interdisciplinary education programs, and knowledge-sharing platforms will be vital to building human capital and technical expertise. Educational outreach can also foster broader awareness and stakeholder engagement across the value chain.

- Comparative assessment with crop-based biorefineries

To further substantiate the outcomes of this study, future research should include comparative analyses between seaweed-based and conventional crop-based biorefineries. Such comparisons would reinforce the sustainability argument and help to position macroalgae as a credible and competitive feedstock within the broader bioeconomy framework.

- Critical final remark – the market demand imperative

One of the most pressing recommendations emerging from this research is the urgent need for a comprehensive market demand analysis for the products derived from the cascade biorefinery. While this Thesis confirms the technical feasibility and sustainability potential of the CB model, its real-world implementation ultimately depends on the existence of sufficient and sustained market demand. Without a viable market for the final products, even the most efficient and sustainable biorefinery system cannot succeed economically or socially. Future studies should therefore move beyond theoretical modeling and focus on applied market research, including demand forecasting, stakeholder engagement, and policy scenario analyses, to assess the actual necessity, scalability, and competitiveness of the cascade biorefinery system.

REFERENCES

- [1] S. Parsons, M. J. Allen, F. Abeln, M. McManus, and C. J. Chuck, "Sustainability and life cycle assessment (LCA) of macroalgae-derived single cell oils," *J Clean Prod*, vol. 232, pp. 1272–1281, Sep. 2019, doi: 10.1016/j.jclepro.2019.05.315.
- [2] Y. Mao, H. Yang, Y. Zhou, N. Ye, and J. Fang, "Potential of the seaweed *Gracilaria lemaneiformis* for integrated multi-trophic aquaculture with scallop *Chlamys farreri* in North China," *J. Appl. Phycol.*, vol. 21, no. 6, pp. 649–656, Nov. 2009, doi: 10.1007/s10811-008-9398-1.
- [3] R. Araújo *et al.*, "Current Status of the Algae Production Industry in Europe: An Emerging Sector of the Blue Bioeconomy," *Front. Mar. Sci.*, vol. 7, Jan. 2021, doi: 10.3389/fmars.2020.626389.
- [4] DCNA, "Importance of Seagrass and Macroalgae in the Protection of Coastlines," Nov. 01, 2020.
- [5] D. Krause-Jensen and C. M. Duarte, "Substantial role of macroalgae in marine carbon sequestration," *Nature Geoscience* 2016 9:10, vol. 9, no. 10, pp. 737–742, Sep. 2016, doi: 10.1038/ngeo2790.
- [6] M. D. Torres, S. Kraan, and H. Domínguez, "Seaweed biorefinery," Jun. 01, 2019, *Springer Science and Business Media B.V.* doi: 10.1007/s11157-019-09496-y.
- [7] L. Ge, P. Wang, and H. Mou, "Study on saccharification techniques of seaweed wastes for the transformation of ethanol," *Renew Energy*, vol. 36, no. 1, pp. 84–89, Jan. 2011, doi: 10.1016/j.renene.2010.06.001.
- [8] "The European Green Deal – European Commission." Accessed: Apr. 02, 2025. [Online]. Available: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en
- [9] "Communication from the Commission: Towards a strong and sustainable EU algae sector - European Commission." Accessed: Jan. 03, 2025. [Online]. Available: https://oceans-and-fisheries.ec.europa.eu/publications/communication-commission-towards-strong-and-sustainable-eu-algae-sector_en
- [10] "EU4Algae – European Commission." Accessed: Jan. 03, 2025. [Online]. Available: https://maritimeforum.ec.europa.eu/theme/blue-economy-and-fisheries/blue-economy/eu4algae_en
- [11] M. Barbier, B. Charrier, R. Araújo, S. L. Holdt, B. Jacquemin, and C. Rebour, "PHYCOMORPH EUROPEAN GUIDELINES FOR A SUSTAINABLE AQUACULTURE OF SEAWEEDS KEY FACTS PEGASUS".
- [12] K. Spilling, *Biofuels from Algae: Methods and Protocols. Methods in Molecular Biology*, Humana Press. Helsinki, 1980. [Online]. Available: <http://www.springer.com/series/7651>
- [13] E. T. Kostas, J. M. M. Adams, H. A. Ruiz, G. Durán-Jiménez, and G. J. Lye, "Macroalgal biorefinery concepts for the circular bioeconomy: A review on biotechnological developments and future perspectives," *Renewable and Sustainable Energy Reviews*, vol. 151, Nov. 2021, doi: 10.1016/j.rser.2021.111553.
- [14] Y. Li *et al.*, "Optimization study on the hydrogen peroxide pretreatment and production of bioethanol from seaweed *Ulva prolifera* biomass," *Bioresour. Technol.*, vol. 214, pp. 144–149, Aug. 2016, doi: 10.1016/j.biortech.2016.04.090.
- [15] J. B. Guinée, G. Huppes, and R. Heijungs, "Developing an LCA guide for decision support," *Environmental Management and Health*, vol. 12, no. 3, pp. 301–311, Aug. 2001, doi: 10.1108/09566160110392416.
- [16] J. B. Guinée, "Handbook on Life Cycle Assessment Operational Guide to the ISO Standards," *JLCA*, vol. 5, pp. 311–313, 2002.
- [17] M. Bučas, D. Daunys, and S. Olenin, "Recent distribution and stock assessment of the red alga *Furcellaria lumbricalis* on an exposed Baltic Sea coast: Combined use of field survey and modeling methods," *Oceanologia*, vol. 51, no. 3, pp. 341–359, 2009, doi: 10.5697/OC.51-3.359.
- [18] "Total Value Chain Optimization of seaweeds *Furcellaria lumbricalis*, A bioeconomical ALGAE demonstration – BlueBio Cofund." Accessed: Mar. 11, 2025. [Online]. Available: <https://bluebioeconomy.eu/total-value-chain-optimization-of-seaweeds-furcellaria-lumbricalis-a-bioeconomical-algae-demonstration/>
- [19] D. Moher, A. Liberati, J. Tetzlaff, and D. G. Altman, "Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement," *BMJ*, vol. 339, no. 7716, pp. 332–336, Jul. 2009, doi: 10.1136/BMJ.B2535.
- [20] Maciej Serda *et al.*, "IEA Bioenergy Task 42 on Biorefineries: Co-production of fuels, chemicals, power and materials from biomass: IEA Bioenergy Task 42 – Countries Report," *Uniwersytet śląski*, vol. 7, no. 1, pp. 343–354, 2010, doi: 10.2/JQUERY.MIN.JS.
- [21] F. Cherubini, "The biorefinery concept: Using biomass instead of oil for producing energy and chemicals," *Energy Convers. Manag.*, vol. 51, no. 7, pp. 1412–1421, Jul. 2010, doi: 10.1016/j.enconman.2010.01.015.
- [22] A. Golberg, A. Liberzon, E. Vitkin, and Z. Yakhini, "Design and Analysis of Offshore Macroalgae Biorefineries," in *Biofuels from Algae: Methods and Protocols*, 1st ed., 2018, pp. 9–33. doi: 10.1007/7651_2018_127.
- [23] F. Fernand, A. Israel, J. Skjermo, T. Wichard, K. R. Timmermans, and A. Golberg, "Offshore macroalgae biomass for bioenergy production: Environmental aspects, technological achievements and challenges," *Renewable and Sustainable Energy Reviews*, vol. 75, pp. 35–45, Aug. 2017, doi: 10.1016/j.rser.2016.10.046.

- [24] M. Segheta, X. Hou, S. Bastianoni, A. B. Bjerre, and M. Thomsen, "Life cycle assessment of macroalgal biorefinery for the production of ethanol, proteins and fertilizers – A step towards a regenerative bioeconomy," *J. Clean Prod.*, vol. 137, pp. 1158–1169, Nov. 2016, doi: 10.1016/j.jclepro.2016.07.195.
- [25] L. Watson and M. Dring, "Business Plan for the Establishment of a Seaweed Hatchery and Grow-out Farm," 2011.
- [26] M. Mac Monagail and L. Morrison, "The seaweed resources of Ireland: a twenty-first century perspective," *J. Appl. Phycol.*, vol. 32, no. 2, pp. 1287–1300, Apr. 2020, doi: 10.1007/S10811-020-02067-7/FIGURES/3.
- [27] M. Teresa, C. Gómez, and A. Lähteenmäki-Uutela, "European and National Regulations on Seaweed Cultivation and Harvesting," Helsinki, 2021.
- [28] D. Brockmann, C. Pradinaud, J. Champenois, M. Benoit, and A. Hélias, "Environmental assessment of bioethanol from onshore grown green seaweed," *Biofuels, Bioproducts and Biorefining*, vol. 9, no. 6, pp. 696–708, Nov. 2015, doi: 10.1002/bbb.1577.
- [29] M. Zollmann, B. Rubinsky, A. Liberzon, and A. Golberg, "Multi-scale modeling of intensive macroalgae cultivation and marine nitrogen sequestration," *Communications Biology* 2021 4:1, vol. 4, no. 1, pp. 1–11, Jul. 2021, doi: 10.1038/s42003-021-02371-z.
- [30] J. Langlois, J. F. Sassi, G. Jard, J. P. Steyer, J. P. Delgenes, and A. Hélias, "Life cycle assessment of biomethane from offshore-cultivated seaweed," *Biofuels, Bioproducts and Biorefining*, vol. 6, no. 4, pp. 387–404, Jul. 2012, doi: 10.1002/BBB.1330.
- [31] R. P. John, G. S. Anisha, K. M. Nampoothiri, and A. Pandey, "Micro and macroalgal biomass: A renewable source for bioethanol," *Bioresour. Technol.*, vol. 102, no. 1, pp. 186–193, Jan. 2011, doi: 10.1016/J.BIORTECH.2010.06.139.
- [32] M. H. Huesemann, L. J. Kuo, L. Urquhart, G. A. Gill, and G. Roesijadi, "Acetone-butanol fermentation of marine macroalgae," *Bioresour. Technol.*, vol. 108, pp. 305–309, Mar. 2012, doi: 10.1016/J.BIORTECH.2011.12.148.
- [33] S. G. Wi, H. J. Kim, S. A. Mahadevan, D. J. Yang, and H. J. Bae, "The potential value of the seaweed Ceylon moss (*Gelidium amansii*) as an alternative bioenergy resource," *Bioresour. Technol.*, vol. 100, no. 24, pp. 6658–6660, Dec. 2009, doi: 10.1016/J.BIORTECH.2009.07.017.
- [34] J. W. Van Hal, W. J. J. Huijgen, and A. M. López-Contreras, "Opportunities and challenges for seaweed in the biobased economy," *Trends Biotechnol.*, vol. 32, no. 5, pp. 231–233, 2014, doi: 10.1016/j.tibtech.2014.02.007.
- [35] R. Peñalver, J. M. Lorenzo, G. Ros, R. Amarowicz, M. Pateiro, and G. Nieto, "Seaweeds as a Functional Ingredient for a Healthy Diet," *Marine Drugs* 2020, vol. 18, no. 6, p. 301, Jun. 2020, doi: 10.3390/MD18060301.
- [36] I. Michalak and K. Chojnacka, "Seaweeds As a Component of the Human Diet," *Algae Biomass: Characteristics and Applications*, pp. 57–71, 2018, doi: 10.1007/978-3-319-74703-3_6.
- [37] C. B. Singh, K. A. M. Xavier, G. Deshmukhe, V. Gudipati, S. S. Shitole, and A. K. Balange, "Fortification of Extruded Product with Brown Seaweed (*Sargassum tenerimum*) and Its Process Optimization by Response Surface Methodology," *Waste Biomass Valorization*, vol. 9, no. 5, pp. 755–764, May 2018, doi: 10.1007/S12649-017-9831-2.
- [38] R. Kumari, I. Kaur, and A. K. Bhatnagar, "Enhancing soil health and productivity of *Lycopersicon esculentum* Mill. using *Sargassum johnstonii* Setchell & Gardner as a soil conditioner and fertilizer," *J. Appl. Phycol.*, vol. 4, no. 25, pp. 1225–1235, Aug. 2013, doi: 10.1007/S10811-012-9933-Y.
- [39] K. Prasad *et al.*, "Detection and quantification of some plant growth regulators in a seaweed-based foliar spray employing a mass spectrometric technique sans chromatographic separation," *J. Agric. Food Chem.*, vol. 58, no. 8, pp. 4594–4601, Apr. 2010, doi: 10.1021/JF904500E.
- [40] G. Sarkar, N. Jatar, P. Goswami, R. Cyriac, K. Suthindhiran, and M. A. Jayasri, "Combination of different marine algal extracts as biostimulant and biofungicide," vol. 41, no. 9, pp. 1163–1171, May 2018, doi: 10.1080/01904167.2018.1434201.
- [41] R. Villares, E. Fernández-Lema, and M. E. López-Mosquera, "Evaluation of beach wrack for use as an organic fertilizer: Temporal survey in different areas," *Thalassas*, vol. 32, no. 1, pp. 19–36, May 2016, doi: 10.1007/S41208-015-0003-5.
- [42] J. B. Hall, W. W. Seay, and S. M. Baker, "Nutrition and Feeding of the Cow-Calf Herd: Essential Nutrients, Feed Classification and Nutrient Content of Feeds," *Virginia Cooperative Extension*, 2009, [Online]. Available: www.ext.vt.edu
- [43] I. Michalak *et al.*, "Effect of macroalgae enriched with microelements on egg quality parameters and mineral content of eggs, eggshell, blood, feathers and droppings," *J. Anim. Physiol. Anim. Nutr. (Berl.)*, vol. 95, no. 3, pp. 374–387, Jun. 2011, doi: 10.1111/J.1439-0396.2010.01065.X.
- [44] J. A. Aguilar-Briseño *et al.*, "Sulphated polysaccharides from *Ulva clathrata* and *Cladophora okamuranus* seaweeds both inhibit viral attachment/entry and cell-cell fusion, in NDV infection," *Mar. Drugs*, vol. 13, no. 2, pp. 697–712, Feb. 2015, doi: 10.3390/MD13020697.

- [45] G. L. Yan, Y. M. Guo, J. M. Yuan, D. Liu, and B. K. Zhang, "Sodium alginate oligosaccharides from brown algae inhibit *Salmonella* Enteritidis colonization in broiler chickens," *Poult. Sci.*, vol. 90, no. 7, pp. 1441–1448, Jul. 2011, doi: 10.3382/PS.2011-01364.
- [46] B. Abbaspour, S. S. Davood, and A. Mohammadi-Sangcheshmeh, "Dietary supplementation of *Gracilariopsis persica* is associated with some quality related sera and egg yolk parameters in laying quails," *J. Sci. Food Agric.*, vol. 95, no. 3, pp. 643–648, Feb. 2015, doi: 10.1002/JSFA.6844.
- [47] Md. M. Islam *et al.*, "Effect of fermented seaweed by-product supplementation on reproduction of Hanwoo cows and growth and immunity of their calves," *Anim. Prod. Sci.*, vol. 56, no. 11, pp. 1828–1833, Jul. 2015, doi: 10.1071/AN14972.
- [48] P. McDonnell, S. Figat, and J. V. Odoherty, "The effect of dietary laminarin and fucoidan in the diet of the weanling piglet on performance, selected faecal microbial populations and volatile fatty acid concentrations," *Animal*, vol. 4, no. 4, pp. 579–585, Oct. 2010, doi: 10.1017/S1751731109991376.
- [49] L. O'Sullivan *et al.*, "Prebiotics from marine macroalgae for human and animal health applications," *Mar. Drugs*, vol. 8, no. 7, pp. 2038–2064, 2010, doi: 10.3390/MD8072038.
- [50] S. Charoensiddhi, M. A. Conlon, C. M. M. Franco, and W. Zhang, "The development of seaweed-derived bioactive compounds for use as prebiotics and nutraceuticals using enzyme technologies," *Trends Food Sci. Technol.*, vol. 70, pp. 20–33, Dec. 2017, doi: 10.1016/J.TIFS.2017.10.002.
- [51] Miao H Q, Elkin M, Aingorn E, Ishai-Michael R, Stein C A, and Vlodavsky I, "Inhibition of heparanase activity and tumor metastasis by laminarin sulfate and synthetic phosphorothioate oligodeoxynucleotides," *Int. J. Cancer.*, vol. 83, no. 3, pp. 424–431, Oct. 1999, Accessed: Dec. 22, 2022. [Online]. Available: <https://pubmed.ncbi.nlm.nih.gov/10495437/>
- [52] Dalin R, Hiroyuki N, Hideomi A, Takahiro N, and Kazutoshi N, "Study on Antihypertensive and Antihyperlipidemic Effects of Marine Algae," *Fisheries Science*, vol. 60, no. 1, pp. 83–88, 1994, Accessed: Dec. 22, 2022. [Online]. Available: https://www.jstage.jst.go.jp/article/fishsci1994/60/1/60_1_83/_pdf
- [53] J. Winberg, P. C. Ranson, and M. Skropeta, "Selecting Australian marine macroalgae based on the fatty acid composition and anti-inflammatory activity," *J. Appl. Phycol.*, vol. 27, no. 5, pp. 2111–2121, 2015, Accessed: Dec. 22, 2022. [Online]. Available: <http://ro.uow.edu.au/smhpapers/2610>
- [54] W. A. J. P. Wijesinghe, G. Ahn, W. W. Lee, M. C. Kang, E. A. Kim, and Y. J. Jeon, "Anti-inflammatory activity of phlorotannin-rich fermented *Ecklonia* cava processing by-product extract in lipopolysaccharide-stimulated RAW 264.7 macrophages," *J. Appl. Phycol.*, vol. 25, no. 4, pp. 1207–1213, Aug. 2012, doi: 10.1007/S10811-012-9939-5.
- [55] D. Pádua, E. Rocha, D. Gargiulo, and A. A. Ramos, "Bioactive compounds from brown seaweeds: Phloroglucinol, fucoxanthin and fucoidan as promising therapeutic agents against breast cancer," *Phytochem. Lett.*, vol. 14, pp. 91–98, Dec. 2015, doi: 10.1016/J.PHYTOL.2015.09.007.
- [56] M. Murray, A. L. Dordevic, L. Ryan, and M. P. Bonham, "An emerging trend in functional foods for the prevention of cardiovascular disease and diabetes: Marine algal polyphenols," *Crit. Rev. Food Sci. Nutr.*, vol. 58, no. 8, pp. 1342–1358, May 2018, doi: 10.1080/10408398.2016.1259209.
- [57] R. Chandra, R. Parra, and H. M. N. Iqbal, "Phycobiliproteins: A Novel Green Tool from Marine Origin Blue-Green Algae and Red Algae," *Protein Pept. Lett.*, vol. 24, no. 2, pp. 118–125, Aug. 2016, doi: 10.2174/0929866523666160802160222.
- [58] S. Sekar and M. Chandramohan, "Phycobiliproteins as a commodity: Trends in applied research, patents and commercialization," *J. Appl. Phycol.*, vol. 20, no. 2, pp. 113–136, Apr. 2008, doi: 10.1007/S10811-007-9188-1/TABLES/9.
- [59] E. M. Balboa *et al.*, "Potential of antioxidant extracts produced by aqueous processing of renewable resources for the formulation of cosmetics," *Ind. Crops Prod.*, vol. 58, pp. 104–110, 2014, doi: 10.1016/J.INDCROP.2014.03.041.
- [60] V. S. Chang and * Teo, "Evaluation of heavy metal, antioxidant and anti-tyrosinase activities of red seaweed (*Eucheuma cottonii*)," *Int. Food Res. J.*, vol. 23, no. 6, pp. 2370–2373, 2016.
- [61] H. J. Hwang, "Skin Elasticity and Sea Polyphenols," *Seanol Science Center Review*, no. 1, pp. 1–10, 2010, Accessed: Dec. 22, 2022. [Online]. Available: www.seanolscience.org
- [62] V. Godvin Sharmila, M. Dinesh Kumar, A. Pugazhendhi, A. K. Bajhaiya, P. Gugulothu, and J. Rajesh Banu, "Biofuel production from Macroalgae: present scenario and future scope," 2021, *Taylor and Francis Ltd.* doi: 10.1080/21655979.2021.1996019.
- [63] Y. Zhao, N. Bourgougnon, J. L. Lanoisellé, and T. Lendormi, "Biofuel Production from Seaweeds: A Comprehensive Review," *Energies* 2022, vol. 15, no. 24, p. 9395, Dec. 2022, doi: 10.3390/EN15249395.
- [64] J. J. Liu, R. Dickson, H. Niaz, J. W. Van Hal, J. W. Dijkstra, and P. Fasahati, "Production of fuels and chemicals from macroalgal biomass: Current status, potentials, challenges, and prospects," Nov. 01, 2022, *Elsevier Ltd.* doi: 10.1016/j.rser.2022.112954.

- [65] M. Aizawa, K. Asaoka, M. Atsumi, and T. Sakou, "Seaweed bioethanol production in Japan – The ocean sunrise project," *Oceans Conference Record (IEEE)*, 2007, doi: 10.1109/OCEANS.2007.4449162.
- [66] J. V. Lamouroux, "Furcellaria lumbricalis (Hudson) J. V. Lamouroux 1813," 1813, Paris. Accessed: Feb. 10, 2023. [Online]. Available: https://www.algaebase.org/search/species/detail/?species_id=14
- [67] P. Kersen, H. Orav-Kotta, J. Kotta, and H. Kukk, "Effect of abiotic environment on the distribution of the attached and drifting red algae *Furcellaria lumbricalis* in the Estonian coastal sea," in *Estonian Journal of Ecology*, Dec. 2009, pp. 245–258. doi: 10.3176/eco.2009.4.01.
- [68] HELCOM, "Furcellaria lumbricalis," Bundesamt für Naturschutz, 2013.
- [69] "Vetik OÜ." Accessed: Mar. 20, 2023. [Online]. Available: <https://vetik.eu/#about>
- [70] G. Martin, T. Paalme, and K. Torn, "Growth and production rates of loose-lying and attached forms of the red algae *Furcellaria lumbricalis* and *Coccolytus truncatus* in Kassari Bay, the West Estonian Archipelago Sea," in *Hydrobiologia*, Jan. 2006, pp. 107–115. doi: 10.1007/s10750-005-1010-y.
- [71] R. Paoli, B. Bjarnason, T. Ilmjärv, and F. Romagnoli, "Off-Shore and On-Shore Macroalgae Cultivation and Wild Harvesting: An LCA-Based Evaluation from Baltic Sea Region Case Studies," *Environmental and Climate Technologies*, vol. 27, no. 1, pp. 606–626, Jan. 2023, doi: 10.2478/rtuct-2023-0045.
- [72] P. Fasahati, R. Dickson, C. M. Saffron, H. C. Woo, and J. J. Liu, "Seaweeds as a sustainable source of bioenergy: Techno-economic and life cycle analyses of its biochemical conversion pathways," *Renewable and Sustainable Energy Reviews*, vol. 157, Apr. 2022, doi: 10.1016/j.rser.2021.112011.
- [73] F. Romagnoli *et al.*, "Furcellaria lumbricalis macroalgae cascade biorefinery: a Life Cycle Assessment study in the Baltic Sea Region," *J. Clean Prod.*, vol. 478, Nov. 2024, doi: 10.1016/j.jclepro.2024.143861.
- [74] A. Arias *et al.*, "Conceptual design and environmental evaluation of the Biorefinery approach for R-phycoerythrin extraction and purification," *N Biotechnol.*, vol. 86, pp. 73–86, May 2025, doi: 10.1016/j.nbt.2025.01.010.
- [75] A. Giwa, "Comparative cradle-to-grave life cycle assessment of biogas production from marine algae and cattle manure biorefineries," *Bioresour. Technol.*, vol. 244, pp. 1470–1479, Nov. 2017, doi: 10.1016/J.BIORTECH.2017.05.143.
- [76] ISO, "ISO 14044:2006, Environmental management — Life cycle assessment — Requirements and guidelines," 2006, *International Organization for Standardization*. Accessed: Jan. 02, 2023. [Online]. Available: <https://www.iso.org/obp/ui/#iso:std:iso:14044:ed-1:v1:en>
- [77] F. Romagnoli *et al.*, "Microalgae cultivation in a biogas plant: Environmental and economic assessment through a life cycle approach," *Biomass Bioenergy*, vol. 182, Mar. 2024, doi: 10.1016/j.biombioe.2024.107116.
- [78] N. Ferronato, R. Paoli, F. Romagnoli, G. Tettamanti, D. Bruno, and V. Torretta, "Environmental impact scenarios of organic fraction municipal solid waste treatment with Black Soldier Fly larvae based on a life cycle assessment," *Environmental Science and Pollution Research*, vol. 31, no. 12, pp. 17651–17669, Mar. 2024, doi: 10.1007/s11356-023-27140-9.
- [79] "Hyndla." Accessed: Mar. 20, 2023. [Online]. Available: <https://hyndla.is/english/>
- [80] M. Goedkoop, M. Oele, J. Leijting, T. Ponsioen, and E. Meijer, "Introduction to LCA with SimaPro Title: Introduction to LCA with SimaPro," 2016. [Online]. Available: www.pre-sustainability.com
- [81] G. Wernet *et al.*, "The ecoinvent database version 3 (part I): overview and methodology," *Int. J. Life Cycle Assess.*, vol. 21, pp. 1218–1230, 2016, doi: 10.1007/s11367-016-1087-8.
- [82] V. A. Mantri, Y. Shah, & S. Thiruppathi, and S. Thiruppathi, "Feasibility of farming the agarose-yielding red alga *Gracilaria dura* using tube-net cultivation in the open sea along the Gujarat coast of NW India," *Applied Phycology*, vol. 1, no. 1, pp. 12–19, 2020, doi: 10.1080/26388081.2019.1648181.
- [83] M. D. Edwards and M. J. Dring, "Open-sea cultivation trial of the red alga, *Palmaria palmata* from seeded tetraspores in Strangford Lough, Northern Ireland," 2011, doi: 10.1016/j.aquaculture.2011.04.007.
- [84] S. Lin, D. Usino, D. Isaksson, L. Lindblad, and G. Peters, "Life cycle assessment of the use of marine biocides in antifouling paint – A comparison of the environmental profiles between conventional copper-based and innovative Selektepe paint," Gothenburg, 2014.
- [85] S. Fazio, L. Zampori, A. De Schryver, O. Kusche, L. Thellier, and E. Diaconu, "Guide for EF compliant data sets," Luxembourg, 2020.
- [86] Uniworkboats SIA, "Peschereccio a strascico – ST-50 – Uniworkboats SIA – entro bordo / in alluminio." Accessed: Feb. 23, 2023. [Online]. Available: <https://www.nauticexpo.it/prod/uniworkboats-sia/product-66044-539847.html>
- [87] F. Piccinno, R. Hischier, S. Seeger, and C. Som, "From laboratory to industrial scale: a scale-up framework for chemical processes in life cycle assessment studies," *J. Clean Prod.*, vol. 135, pp. 1085–1097, Nov. 2016, doi: 10.1016/j.jclepro.2016.06.164.
- [88] National Center for Biotechnology Information, "PubChem Compound Summary for CID 24346, Sodium disulphite." Accessed: Jul. 19, 2023. [Online]. Available: <https://pubchem.ncbi.nlm.nih.gov/compound/Sodium-disulphite>

- [89] National Center for Biotechnology Information, “PubChem Compound Summary for CID 33258, Allura Red AC.” Accessed: Jul. 19, 2023. [Online]. Available: <https://pubchem.ncbi.nlm.nih.gov/compound/Allura-Red-AC>
- [90] D. Saha and S. Bhattacharya, “Hydrocolloids as thickening and gelling agents in food: A critical review,” Dec. 2010. doi: 10.1007/s13197-010-0162-6.
- [91] K. Hayashi, G. Gaillard, and T. Nemecek, “Life cycle assessment of agricultural production systems: Current issues and future perspectives,” *Good Agricultural Practice (GAP) in Asia and Oceania*, 2005, [Online]. Available: <https://www.researchgate.net/publication/240634920>
- [92] A. E. Nilsson, K. Bergman, L. P. Gomez Barrio, E. M. Cabral, and B. K. Tiwari, “Life cycle assessment of a seaweed-based biorefinery concept for production of food, materials, and energy,” *Algal Res.*, vol. 65, p. 102725, Jun. 2022, doi: 10.1016/J.ALGAL.2022.102725.
- [93] I-REC Standard Foundation, “Understanding EAC Schemes and Roadmaps for Their Development,” 2020.
- [94] M. A. J. Huijbregts *et al.*, “ReCiPe 2016 v1.1. A harmonized life cycle impact assessment method at midpoint and endpoint level,” Bilthoven, 2017. [Online]. Available: www.rivm.nl/en
- [95] M. Z. Hauschild, R. K. Rosenbaum, and S. I. Olsen, *Life Cycle Assessment Theory and Practice*. 2018.
- [96] “Orbis.” Accessed: Nov. 24, 2024. [Online]. Available: <https://login.bvdinfo.com/R1/Orbis>
- [97] “teatmik.ee.” Accessed: Nov. 24, 2024. [Online]. Available: <https://www.teatmik.ee/>
- [98] “Sweden | Alfa Laval.” Accessed: Nov. 24, 2024. [Online]. Available: <https://www.alfalaval.se/>
- [99] Tommie. Ponsioen, Gohar. Nuhoff-Isakhanyan, Theun. Vellinga, Willy. Baltussen, Koen. Boone, and Geert. Woltjer, *Monetisation of sustainability impacts of food production and consumption*. Wageningen Economic Research, 2020.
- [100] C. Benoit Norris *et al.*, “Guidelines for Social Life Cycle Assessment of Products and Organizations 2020,” 2020.
- [101] International Organization of Standardization, “ISO 14075:2024 – Environmental management – Principles and framework for social life cycle assessment,” Oct. 2024.
- [102] J. Martínez-Blanco *et al.*, “Application challenges for the social Life Cycle Assessment of fertilizers within life cycle sustainability assessment,” *J. Clean Prod.*, vol. 69, pp. 34–48, Apr. 2014, doi: 10.1016/j.jclepro.2014.01.044.
- [103] G. Norris, “Chapter 8: The Social Hotspots Database Context of the SHDB,” Nov. 2015. [Online]. Available: <https://www.researchgate.net/publication/287215286>
- [104] L. Tonucci, A. Mascitti, A. M. Ferretti, F. Coccia, and N. d’Alessandro, “The Role of Nanoparticle Catalysis in the Nylon Production,” *Catalysts*, vol. 12, no. 10, p. 1206, Oct. 2022, doi: 10.3390/CATAL12101206/S1.
- [105] C. B. Norris, D. Aulisio, and G. A. Norris, “Working with the Social Hotspots Database – Methodology and findings from 7 social scoping assessments,” in *Leveraging Technology for a Sustainable World – Proceedings of the 19th CIRP Conference on Life Cycle Engineering*, Springer Berlin Heidelberg, 2012, pp. 581–586. doi: 10.1007/978-3-642-29069-5_98.
- [106] W. Kloepffer, “Life cycle sustainability assessment of products (with Comments by Helias A. Udo de Haes, p. 95),” *International Journal of Life Cycle Assessment*, vol. 13, no. 2, pp. 89–95, Feb. 2008, doi: 10.1065/LCA2008.02.376/METRICS.
- [107] C.-L. Hwang and K. Yoon, “Methods for Multiple Attribute Decision Making,” pp. 58–191, 1981, doi: 10.1007/978-3-642-48318-9_3.
- [108] M. Grinberg, R. Ackermann, and M. Finkbeiner, “Ecological scarcity method: Adaptation and implementation for different countries,” *Environmental and Climate Technologies*, vol. 10, no. 1, pp. 9–15, 2012, doi: 10.2478/v10145-012-0019-5.
- [109] M. Troell, P. J. G. Henriksson, A. H. Buschmann, T. Chopin, and S. Quahe, “Farming the Ocean—Seaweeds as a Quick Fix for the Climate?” 2022, *Taylor and Francis Ltd*. doi: 10.1080/23308249.2022.2048792.
- [110] F. Gkatzoglou, T. Papadimitriou, and P. Gogas, “Fuel Price Networks in the EU,” *Economies* 2024, vol. 12, no. 5, p. 102, Apr. 2024, doi: 10.3390/ECONOMIES12050102.



Riccardo Paoli was born in 1996 in Varese, Italy. He earned a Bachelor's degree in Environmental and Workplace Safety Engineering (2018) and a Master's degree in Environmental and Workplace Sustainability Engineering (2021) from the University of Insubria. Since 2021, he has been a researcher at the Institute of Energy Systems and Environment at Riga Technical University and is currently working as a Sustainability Engineer at ABB. During his doctoral studies, Riccardo was a visiting student at the University of Texas at Arlington and received the Young Scientist Award at the Baltic Sea Science Day in 2022. His research focuses on cleaner production, circular economy approaches, and sustainability strategies, particularly in complex value chains and emerging technologies.