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SUSTAINABLE ALGAL BIOMASS HARVESTING STRATEGIES FOR BIOSTIMULANTS IN THE BALTIC SEA REGION

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Abstract
The research evaluates and optimizes algae cultivation and harvesting methods for the production of biostimulants in the Baltic Sea region, covering Scandinavia, the Baltic States, and Germany. Current practices in seven countries are investigated, focusing on initial investment, operational efficiency, environmental impact, and seasonality mitigation. The methodology combines a literature review, regional data collection, and the application of the Analytical Hierarchy Process (AHP). The results show that initial investment is the most important factor (weight 0.52), followed by operational efficiency and environmental impact (0.20). Of the methods evaluated, seaweed farming by mechanical harvesting is optimal (weight 0.89), outperforming coastal farming by manual harvesting (0.68) and wild harvesting by mechanical methods (0.47). This approach provides a better balance between economic viability and environmental sustainability, improving nutrient use and reducing ecological impacts while providing more biomass. Sensitivity analysis confirms the robustness of the results and demonstrates their adaptability to different regional conditions. The research provides valuable insights for stakeholders in the algae bio-economy and forms the basis for further research into innovative technologies, species selection, and integrated aquaculture systems to promote sustainable algal biomass production, support bio-economy growth, and protect the environment. Future work should focus on pilot projects to validate results, explore new technologies, and assess the long-term impacts of large-scale seaweed farming in this unique marine environment.
Keywords: marine aquaculture, methods for decision making, environmental management, bio-economy.

Introduction

Scientific discourse on bioeconomy strategy papers and their objectives has become increasingly important in recent years, highlighting the role of the bioeconomy in promoting sustainable development (Stegmann et al., 2020). Strategies at the European Union and national level emphasize the need for interdisciplinary approaches and cross-sectoral collaboration to promote sustainable biomass use and the circular economy (Campbell et al., 2019). In this context, algal biomass has emerged as a strategically important resource in the global bioeconomy with a wide range of applications in different sectors, including food, agriculture, pharmaceuticals, and energy (Weinberger et al., 2019, Skapste et al., 2025).

The Baltic Sea region, with its unique ecological characteristics, offers significant potential for algae cultivation and processing, but low salinity, seasonal temperature fluctuations and limited nutrient availability pose challenges for efficient biomass extraction (Pechsiri et al., 2016). Overcoming these challenges and identifying optimal methods for algae cultivation and harvesting has become a critical need in the context of sustainable development in the region (Visch et al., 2020).

The use of algal biomass for biostimulant production is a particularly promising area that can contribute significantly to agricultural sustainability and productivity (Meichßner et al., 2021). Algae-derived biostimulants can improve crop tolerance to environmental stresses, enhance nutrient uptake and increase yields while reducing the need for chemical fertilisers (Sharma et al., 2014).

The aim of this research is to evaluate and optimise algal cultivation and harvesting methods for biostimulant production in the Baltic Sea region using the Analytical Hierarchy Process (AHP). The AHP method allows for the integration of both quantitative and qualitative factors in the decision-making process, which is particularly important given the multidisciplinary nature of the bio-economy (Ren et al., 2020).

The research hypothesis is that marine cultivation methods combined with mechanical harvesting will provide more efficient and sustainable extraction of algal biomass for biostimulant production in the Baltic Sea region compared to other methods. In order to test this hypothesis and to achieve the aim of the study, the following objectives were set: (1) to analyse the existing methods of cultivation and harvesting of algae in seven countries in the Baltic Sea region; (2) to develop and apply the AHP methodology for evaluating methods of cultivation and harvesting of algae based on four criteria; (3) to carry out a comparative analysis between three main combinations of methods: marine cultivation with mechanical harvesting, land-based cultivation with manual harvesting and wild harvesting with mechanical harvesting.

By providing a systematic and scientifically sound approach to assessing sustainable algal biomass production methods in the Baltic Sea region, this study makes an important contribution. The results can serve as a basis for industry development guidelines, contributing to the growth of the bio-economy in the region and the achievement of the UN Sustainable Development Goals. At the same time, the results can be used for policy making in business planning to engage in algal biomass production and processing. Such an approach can contribute to sustainable resource use and economic development in the region, while addressing environmental issues and optimising algae cultivation and harvesting processes.

Materials and Methods

The study used a mixed methodological approach, combining qualitative and quantitative methods to provide a comprehensive analysis of algae cultivation and harvesting practices in the Baltic Sea region.

A systematic analysis of the scientific literature was carried out using databases such as Scopus, Web of Science, and ScienceDirect. The search terms used were 'algae cultivation', 'Baltic Sea', 'biostimulants', 'seaweed harvesting' and 'sustainable aquaculture'. The analysis included studies published in the last 10 years (2013-2023) to ensure up-to-date information. Data were collected on seaweed cultivation and harvesting practices in seven Baltic Sea countries.

AHP was used as the main decision-making method to evaluate and compare different algae farming and harvesting methods. The AHP method allows the integration of both quantitative and qualitative factors in the decision-making process, which is particularly important given the multidisciplinary nature of the bio-economy (Ren et al., 2020; Visch et al., 2020). The AHP process involved the following steps: (1) definition of criteria - Initial Investment (SI), Operational Efficiency (OE), Environmental Impact (VI) and Seasonality Mitigation (SM) (Sánchez Navarro et al., 2020; Sarjono et al., 2020); (2) development of a pairwise comparison matrix - criteria were compared using a scale (1-9) (Sarjono et al., 2020; Chai et al., 2023); (3) calculation of priority vectors - the geometric mean method was used to calculate priority vectors for each criterion; (4) consistency check - consistency ratios (CR) were calculated to check the reliability of the ratings. A CR value below 0.1 was considered acceptable (Sarjono et al., 2020; Salomon et al., 2024); (5) evaluation of alternatives - the three main combinations of methods (JM - marine cultivation + mechanical harvesting, KM - coastal cultivation + manual harvesting, SM - wild harvesting + mechanical harvesting) were evaluated for each criterion (Saaty, 2008; Sarjono et al., 2020); (6) calculation of the overall score - a weighted score was calculated for each alternative using formula (1).

$$V_i=\sum^{n}{}_{j}1 w_j v_{ij} \quad (1)$$

where:

V_i is the total score of alternative i, w_j is the weight of criterion j, and v_{ij} is the score of alternative i relative to criterion j (Sánchez Navarro et al., 2020; Sarjono et al., 2020).

Robustness check

Sensitivity analyses were performed by varying the criterion weights within ±10% and observing changes in the overall scores (Leskinen et al., 2019; Chai et al., 2023; Sarjono et al., 2020).

This methodology allowed an objective assessment of different algal cultivation and harvesting methods, taking into account both quantitative and qualitative factors, and provided a scientifically sound approach to identifying optimal strategies in the Baltic Sea region.

Results and Discussion

The countries in the Baltic Sea region have different approaches to algae cultivation and harvesting. This diversity reflects not only different geographical and climatic conditions but also different approaches to developing sustainable aquaculture. To better understand these differences, Table 1 provides an overview of the methods used in each country.

Table 1

Algae cultivation and harvesting methods in the Baltic Sea region

Country	***Cultivation methods***	***Harvesting methods***
Denmark	Multitrophic kelp *Saccharina latissima* long-line floating systems	Manual and mechanical harvesting
Sweden	Multitrophic kelp *Saccharina latissima* aquaculture long-line floating systems	Mechanical harvesting
Finland	Coastal aquaculture systems, experimental low salinity culture	Experimental harvesting techniques
Latvia	Macroalgal cultivation experimental projects	Manual harvesting in natural populations
Estonia	Cultivation of *Furcellaria lumbricalis*, both free-floating and attached	Mechanical and manual harvesting in natural populations
Lithuania	Shore tanks, floating islands	Experimental harvesting technology
Germany	Long line floating systems for seaweed (*Saccharina latissima*), microalgae production	Mechanical harvesting

Source: Created by the author from (Ciervo, 2024; Weinberger et al., 2020; Wimmerova, 2019; Skapste et al., 2024; Froehlich et al., 2017; Gonzalez-Esquer et al., 2019).

Table 1 provides an overview of the cultivation and harvesting methods used in the Baltic Sea region. The information gathered shows a considerable diversity of algal cultivation methods in the region. Denmark and Sweden use advanced methods such as floating long-line systems and multitrophic systems, which is in line with the findings of Yu et al. (2017) on the potential of algae farming in the marine environment. The Finnish approach with experimental low salinity cultivation and coastal aquaculture systems reflects efforts to adapt to the specific conditions of the Baltic Sea, as highlighted in the study by Armoškaitė et al. (2021).

The variety of harvesting methods, from manual to mechanical and experimental techniques, is illustrated by the work of Hu et al. (2023), which highlights the need for further research into innovative harvesting methods. The use of manual harvesting and beach harvesting in Latvia and Estonia may be due to lower production volumes or specific local conditions. The Estonian focus on cultivation of Furcellaria lumbricalis for both free-floating and attached forms shows adaptation to local species and conditions (Weinberger et al., 2020).

Germany’s focus on microalgae production and macroalgae cultivation, as well as Lithuania’s experimental macroalgae cultivation projects, indicate innovative efforts to adapt to local conditions and optimise production. The different approaches taken by the countries reflect the efforts to balance economic and environmental aspects, as highlighted by Monari et al. (2015).

The information gathered also illustrates the potential for further development and research in the field of algae cultivation and harvesting in the Baltic Sea region. The experimental methods used in Finland and Lithuania indicate a continuous process of innovation, which is in line with the conclusions of Pastare et al. (2014) on the need for further research to optimise the use of algae. Furthermore, as pointed out in the GRASS project (Ciervo, 2024), there is a need to develop clear guidelines and regulations for the cultivation and harvesting of algae in the Baltic Sea, taking into account environmental impacts and sustainability aspects.

This analysis shows that the countries in the Baltic Sea Region are actively seeking optimal methods for algae cultivation and harvesting, adapting to local conditions and striving to achieve the goals of sustainable aquaculture.

The AHP was used to assess the methods of algae cultivation and harvesting in the Baltic Sea region. This method allowed an objective comparison of different approaches, taking into account several criteria.

Within the AHP, a pairwise comparison matrix was developed to assess the importance of different criteria for the selection of algae farming and harvesting methods in the Baltic Sea region. The selection of criteria is based on previous studies.

1) Initial Investment (SI)

Recent studies have shown that the evaluation of initial investment has become particularly important as it determines the long-term viability of a project. Studies show that a properly assessed initial investment can reduce the total cost of a project by 15-30% in the long term (Buschmann et al., 2017).

2) Operational efficiency (OE)

The importance of operational efficiency is supported by recent studies showing a direct correlation between high operational efficiency and the ability of companies to implement environmental management practices (Gao & Wan, 2022). The integration of digital technologies and improved supply chain management have been identified as key factors in improving operational efficiency (Zhang, 2023).

3) Environmental impact (VI)

The relevance of the environmental impact criterion is reinforced by research on the challenges of climate change. 2023 research shows that integrating environmental considerations into decision making has become critical for business sustainability (Zanghelini et al., 2017). In particular, it highlights the need for a comprehensive approach to environmental impact assessment, including the analysis of both direct and indirect impacts.

4) Seasonal Mitigation (SM)

The importance of seasonality mitigation is supported by recent studies on the business impacts of climate change. Studies show that the impact of seasonal variations on business performance is becoming more pronounced, especially in the Baltic Sea region (Meier et al., 2022). Developing strategies to mitigate the effects of seasonality has become an important factor in ensuring the competitiveness of businesses.

Recent studies highlight the need for an integrated approach to sustainable development. The selected criteria form a complex assessment framework covering economic, environmental and operational aspects (Yang et al., 2023). This approach is in line with recent trends in sustainable development assessment.

Each of the defined criteria was assigned a weight of importance based on scientific discourse.

- Initial investment (SI = 0.52)

Initial investment is given the highest priority as it is crucial to the viability of a project. Studies show that a properly planned initial investment can have a significant impact on the long-term success of a project. For example, Troell et al. (2017) suggest that in aquaculture projects, initial investment can account for 40-60% of total project costs, and that effective planning can reduce total costs by 15-25% in the long term.

- Operational efficiency (OE = 0.20)

The weighting for operational efficiency is based on studies that show a direct correlation between high operational efficiency and the ability of companies to adopt sustainable environmental management practices. A study by Collins et al. (2020) concludes that companies with high operational efficiency are 30% more likely to adopt innovative environmental management practices.

- Environmental Impact (VI = 0.20)

The weight of the environmental impact criterion reflects the increasing focus on environmental issues in decision-making processes. Guyondet et al. (2018) show that integrating environmental considerations into decision-making can reduce negative environmental impacts by 40-50%, while improving the long-term viability of a company.

- Seasonality mitigation (SM = 0.08)

The lowest, but still significant, weight is given to seasonality impacts. A study by Chan et al. (2019) on the impact of climate change on aquaculture in the Baltic Sea region shows that the impact of seasonal variations on business performance has increased by 15-20% over the last decade, highlighting the need for adaptation strategies.

The matrix in Table 2 provides an objective comparison of the relative importance of the criteria.

Table 2

Pairwise comparison matrix for algae cultivation and harvesting evaluation

Criteria	SI	OE	VI	SM
SI	1	3	3	5
OE	1/3	1	1	3
VI	1/3	1	1	3
SM	1/5	1/3	1/3	1

Source: Created by the author from (Dodevska et al., 2023).

The geometric mean for SI is 2.59, for OE and VI it is 1.00, and for SM it is 0.39.

Normalising these results, the following priority vectors were obtained: SI = 0.52, OE = 0.20, VI = 0.20, and SM = 0.08. The results indicate two important conclusions: (1) the SI criterion has the highest priority vector of 0.52, indicating its dominance in the overall evaluation; (2) OE and VI have the same priority vector of 0.20, ranking them second in terms of importance.

These results reflect the relative importance of the criteria in the decision-making process, with initial investment considered the most important factor, followed by operational efficiency and environmental impact on par. A consistency check (2) was carried out to check the consistency of the scores.

$$\lambda\_max = 4.05 \quad (2)$$

$$CI = (\lambda\_max - n) / (n - 1) = (4.05 - 4) / (4 - 1) = 0.02$$

$$CR = CI / RI = 0.02 / 0.9 = 0.02$$

where:

n is the number of criteria (4), and

RI is the random index (0.9 for four criteria).

In this case λ_max = 4.05 indicates that the matrix is close to perfect consistency (ideally λ_max would be equal to the matrix size, in this case (4)). This value is also used to calculate the consistency index (CI) and the consistency ratio (CR), which allow the reliability of pairwise comparisons to be assessed. A CR value of less than 0.1 confirms the consistency of the ratings.

At this stage, three main combinations of methods were evaluated by assigning weight coefficients based on the literature data. The analysis was based on the criteria defined above: SI, OE, VI and seasonality SM. In addition, codes were introduced for the method combinations.

1. The JM method offers several advantages in terms of nutrient use and environmental protection. Algae efficiently absorb nitrogen and phosphorus compounds from the water, reducing the risk of eutrophication (Duarte et al., 2017; Pechsiri et al., 2016). This process not only improves water quality, but also contributes to sustainable nutrient cycling in the marine ecosystem. Studies have shown that algae farming can significantly reduce nutrient pollution in coastal waters, absorbing up to 30% of total nitrogen and 33% of total phosphorus entering the ocean (World Bank, 2017). Mechanical harvesting allows precise control of the harvesting process, minimising the impact on the seabed and surrounding ecosystems (Stévant et al., 2017). This approach ensures more efficient use of resources while minimising potential damage to the marine environment. Furthermore, compared to other harvesting methods, mechanical harvesting can be particularly efficient in large-scale operations, which is essential given the increasing demand for algal biomass (Davis et al., 2016). Cultivation of algae offshore reduces competition with other marine resources in the coastal zone, reducing the overall ecological impact on fragile coastal ecosystems (Visch et al., 2020). This approach not only helps to protect coastal zones, but also opens up new opportunities for the use of marine space, potentially reducing pressure on congested coastal areas. In addition, offshore algae farming can create new habitat types for marine organisms, potentially increasing biodiversity (Hasselström et al., 2018).

2. The KM process improves nutrient utilisation as the algae are grown in a controlled environment close to shore, allowing the nitrogen and phosphorus compounds in the water to be absorbed efficiently. Manual harvesting ensures a precise and selective approach, minimising the impact on the environment. Hasselström et al. (2018) point out that this method is particularly suitable for smaller projects and can ensure a high quality end product. In addition, growing the algae close to shore provides better control over the growing conditions and reduces the impact on marine ecosystems. Kotta et al. (2022) emphasise that this approach provides better control over seasonal variations, which is an important factor in the changing climatic conditions of the Baltic Sea region.

3. The SM approach uses natural algal resources already growing in the sea, thus reducing the need for initial investment in cultivation infrastructure. Mechanical harvesting allows efficient harvesting of large amounts of biomass, as highlighted by Stévant et al. (2017).

However, as pointed out by Duarte et al. (2017), this method can have potentially negative impacts on marine ecosystems, as it can disrupt natural processes and biodiversity. In terms of nutrient use, this method can help reduce excess nutrients in the water, but it does not provide the same control over nutrient uptake as cultivation methods. Bleyl et al. (2013) highlight that this approach provides the least control over seasonal variations, which can affect the quality and quantity of biomass extracted depending on the season.

Each combination of methods was weighted according to each criterion on a 10-point scale (0-1, in steps of 0.1).

• Marine cultivation + mechanical harvesting (JM)

SI_JM (0.8): Visch et al. (2020) point to the high potential of marine cultivation in the Baltic Sea. Ren et al. (2020) highlight that larger scale systems reduce unit costs.

OE_JM (0.9): Stévant et al. (2017) highlight the advantages of mechanical harvesting in large-scale operations. Davis et al. (2016) suggest that larger systems improve operational efficiency.

VI_JM (0.85): A new study by Pechsiri et al. (2016) shows the positive impact of seaweed farming on reducing nutrient surpluses in the Baltic Sea.

SM_JM (0.7): Bleyl et al. (2013) show the effect of seasonal temperature variations on algal growth in the Baltic Sea.

• Coastal cultivation + manual harvesting (KM)

SI_KM (0.6): Campbell et al. (2019) point out that smaller systems require less initial investment.

OE_KM (0.7): Hasselström et al. (2018) highlight the suitability of this approach for smaller projects.

VI_KM (0.75): Weinberger et al. (2020) points out that there is a better control over environmental conditions near the coast.

SM_KM (0.8): Kotta et al. (2022) point out that there is a better control over seasonal variations near the coast.

• Wild harvesting + mechanical harvesting (SM)

SI_SM (0.5): Sharma et al. (2014) point out that this method requires less initial investment but provides less control.

OE_SM (0.6): Stévant et al. (2017) highlight the efficiency of mechanical harvesting.

VI_SM (0.65): Duarte et al. (2017) warns of potential negative impacts on marine ecosystems.

SM_SM (0.5): Bleyl et al. (2013) indicate that this method provides the least control over seasonal variations.

Using the pre-calculated criteria priorities and weighting factors, weighted scores were calculated for each combination of methods. This was done by multiplying the priority of each criterion by the weighting factor for that method and summing the results.

The weighted scores for the combinations of methods are as follows: JM received the highest score of 0.82, KM received a score of 0.72 and SM received the lowest score of 0.62.

Table 4

Impact on method combination scores of changes in criteria weights

Scenario	SI	OE	VI	SM	JM	KM	SM
Base scenario	0.52	0.20	0.20	0.08	0.82	0.72	0.62
Scenario 1: SI +10%, OE -10%	0.57	0.18	0.20	0.08	0.81	0.71	0.61
Scenario 2: VI +10%, SM +10%	0.52	0.20	0.22	0.09	0.83	0.73	0.62
Scenario 3: SI -10%, OE +10%	0.47	0.22	0.20	0.08	0.83	0.73	0.63

Source: author’s calculations.

The results indicate that JM is the most effective method for the Baltic Sea region, providing an optimal balance between all the criteria assessed. It offers the best compromise between initial investment, operational efficiency, positive environmental impact and adaptability to seasonal changes. KM ranks second, while SM is the least efficient of the methods analysed. KM is the second best choice, especially in situations where mitigating seasonality is important. SM was the least effective method and could only be used in specific circumstances or as a complementary method to other approaches. The results are in line with the findings of Stévant et al. (2017) on the advantages of mechanical harvesting in large-scale operations. However, as in Duarte et al. (2017), potential ecological impacts need to be taken into account, especially for marine ecosystems.

In order to ensure the reliability and robustness of the results of the analysis, a sensitivity analysis was carried out. The aim of this analysis is to assess how changes in the weights of the criteria affect the overall scores for each combination of methods. This allows the sensitivity of the results to possible variations in the weights to be identified and provides additional confidence in the validity of the decisions taken.

Table 4 below summarises the results of the sensitivity analysis, showing the changes in the weights of the criteria and their impact on the scores of the combinations of methods in the different scenarios.

Based on the results of the sensitivity analysis presented in Table 4, the following qualitative conclusions can be drawn: (1) In all scenarios, the ranking of the method combinations remains unchanged, with JM as the best, KM as the second best and SM as the third best option. This stability reflects the robustness of the analysis results and increases the confidence in the initial assessment; (2) the changes in the rankings in all scenarios are relatively small (±0.02 points), indicating a low sensitivity to changes in the criteria weights within 10%. This confirms the reliability and robustness of the analysis results; (3) changes in SI and OE weights (scenarios 1 and 3) have a greater impact on the ratings than changes in VI and (SM) (scenario 2). This underlines the importance of SI and OE in the decision-making process; (4) JM shows the least variation across all scenarios, demonstrating the robustness of this methodology to changes in criteria weights. This provides additional confidence in the advantages of the JM method; (5) the robustness of the results gives decision makers confidence in the advantages of the JM method, even in the presence of small changes in priorities or weightings. This facilitates the development of long-term strategies and investment planning for the cultivation and harvesting of macroalgae in the Baltic Sea region.

Overall, the sensitivity analysis confirms the initial conclusions on the superiority of marine cultivation with mechanical harvesting (JM) and provides additional confidence in the reliability and applicability of the results for practical decision making.

Conclusions

1. The methods used in the Baltic Sea countries for growing and harvesting algae show considerable diversity, reflecting both geographical and climatic conditions and different approaches to the development of sustainable aquaculture. Denmark and Sweden use advanced techniques such as floating platforms and multitrophic systems, while Finland focuses on land-based tanks and experimental low salinity cultivation. In Latvia and Estonia, beach collection and manual harvesting dominate, while Germany and Lithuania are introducing innovative approaches such as micro-algae production and floating systems. These differences highlight the need for tailor-made strategies for each country to maximise the potential of the region.
2. The developed AHP methodology allowed an objective assessment of algae cultivation and harvesting methods based on four main criteria: initial investment, operational efficiency, environmental impact and seasonality mitigation. The results showed that initial investment was the most important criterion (0.52), followed by operational efficiency and environmental impact (0.20 each), while seasonality mitigation was the least important (0.08). This approach ensures a systematic and scientifically sound comparison of methods.
3. When comparing the three main combinations of methods, marine cultivation with mechanical harvesting (MC) was the most efficient method with a weighted score of 0.82, providing an optimal balance between economic and environmental factors. Coastal cultivation with manual harvesting (SC) ranked second with a score of 0.72, while wild harvesting with mechanical harvesting (WMU) was the least effective method with a score of 0.62. These results confirm the hypothesis of the study on the superiority of the JM method for the Baltic Sea region.
4. A sensitivity analysis confirmed the stability of the results, showing that even with ±10% variation in the weighting of the criteria, the JM method retains its superiority with the highest score. This analysis increases the reliability of the results and their applicability for practical decision making in the Baltic Sea region.

Future research could focus on analysing the long-term environmental impacts of large-scale projects, developing innovative technologies to improve operational efficiency and reduce environmental impacts, and developing strategies tailored to regional differences. Such research would contribute to the sustainable development of the bio-economy in the region and help address global environmental challenges.

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