WP9 - Blue bio-based industry

D9.2 "Report for Stakeholders: Blue bio-based sector-wide recommendations (microalgae focus)"

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1 Executive summary

The ALIGNED project has provided a selection of scientifically sound methods for assessing biobased products, which is defined within the project as the ALIGNED framework. The framework was subsequently applied to a series of case studies across five sectors, including microalgal biotechnology, which is positioned as an emerging technology within the broader chemical sector. This work was conducted in ALIGNED by the partners A4F and AAU. Based on the results and insights derived from the application to the case study, as well as based on the feedback received from stakeholders in the chemical sectors during the stakeholder involvement surveys and workshops, several recommendations were derived for stakeholders in the emerging microalgal industry. These recommendations target the analysis of the environmental performance of microalgal-based products via Life Cycle Assessment (LCA).

It is specifically recommended to: 1) Ensure high-quality and standardized data collection across the value chain, 2) Promote harmonization between standards and methodological alignment, 3) Continuously update and refine the data from the developed modeling systems, 4) Identify sustainability hotspots and assess alternative scenarios for improvement, 5) Foster industrial symbiosis and circular economy integration approaches, and 6) Apply the -1/+1 method and keep clear carbon flow tracking.

The ALIGNED project results can support the implementation of these recommendations by providing guidance regarding the sharing of life-cycle data, development of foreground and background LCA models for emerging biobased technologies, carbon accounting for biogenic carbon and temporal storage, and uncertainty analysis in LCA studies of biobased products.

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2 Overview of the sector

Algae can be characterized as a broad collection of photosynthetic organisms present in almost every watery habitat. They range in size from microscopic single-celled organisms (less than 3 µm) to huge multicellular forms (more than 30 m). Algae are divided into two types: microalgae and macroalgae. Microalgae are single-celled organisms found in both saltwater and freshwater habitats, while macroalgae are multicellular organisms that can be found in freshwater and maritime habitats.

Microalgal biotechnology is comparable to conventional agriculture; however, it offers great sustainability due to the rapid growth rate of microalgae and high areal productivity, without competing for agricultural land (Saratale et al, 2022). As a consequence of the rapid growth rate of microalgae, higher productivity than traditional crops is achieved, and unlike traditional crops, microalgae can grow in climates and areas inappropriate for agricultural purposes (e.g., desert and seashore lands) (Sahni et al, 2019). Microalgae biomass, in a similar concept to agriculture-derived biomass, can be applied in many different sectors, such as food, feed, pharma, cosmetics, biomaterials, fertilizers, or bioenergy, and its production can be used as an ecosystem service tool for the treatment/bioremediation of gas and liquid effluents or carbon capture (Fernández et al, 2021).

According to the European Algae Biomass Association (EABA), worldwide production of microalgae biomass is approximately 130,000 tonnes of dry weight per year, valued at approximately €2.6 billion, with more than 75% coming from China. European yield is 0.5% of the worldwide production, while some nations, such as the UK, have virtually no industrial production of microalgae (European Commission, 2023). The European algae sector includes 225 companies that produce microalgae (33%) and macroalgae (67%) (Araújo et al, 2021).

To address this gap and support the expansion of microalgae production in Europe, it is needed to rely on experienced companies like A4F, a biotechnology company based in Portugal with more than 20 years of experience in algae research and development, and algae production at an industrial scale. A4F specializes in the design, construction, operation, and transfer (DBOT) of algae production units, from research and demonstration to industrial production, using different technologies that best suit the client's objectives and needs. As a company involved in many European R&D projects, A4F has developed close relationships over the years with the best national and international universities and research groups in the field of algae biotechnology, as well as with the world's largest producers and distributors, making the company the first choice for contracts to set up industrial algae production units.

A4F was responsible for the implementation and commissioning of the largest microalgae production platform in Europe, the ALGATEC Eco Business Park, in Póvoa de Santa Iria (close to Lisbon, Portugal), with a production capacity of 270 tonnes/yr of microalgae biomass and extraction of high-value products. A4F acts as a site manager of the ALGATEC Eco Business Park and as an operations manager for the microalgae production and refining activities.

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For the case under study, the focus was on the assessment of the environmental performance of the biorefinery of products targeting the food and feed markets. The products obtained through the biorefinery can potentially replace similar compounds in the food and feed market, which are, however, produced via pathways of lower environmental performance, thus showing a mitigation potential. Figure 1 shows an overview of the system for which a Life Cycle Assessment (LCA) study was conducted by A4F and AAU, an example derived from the operation of the ALGATEC Eco Business Park platform. The study aimed to give some insights into the environmental impact of the microalgae biorefinery while assessing alternative scenarios for optimizing the processes.

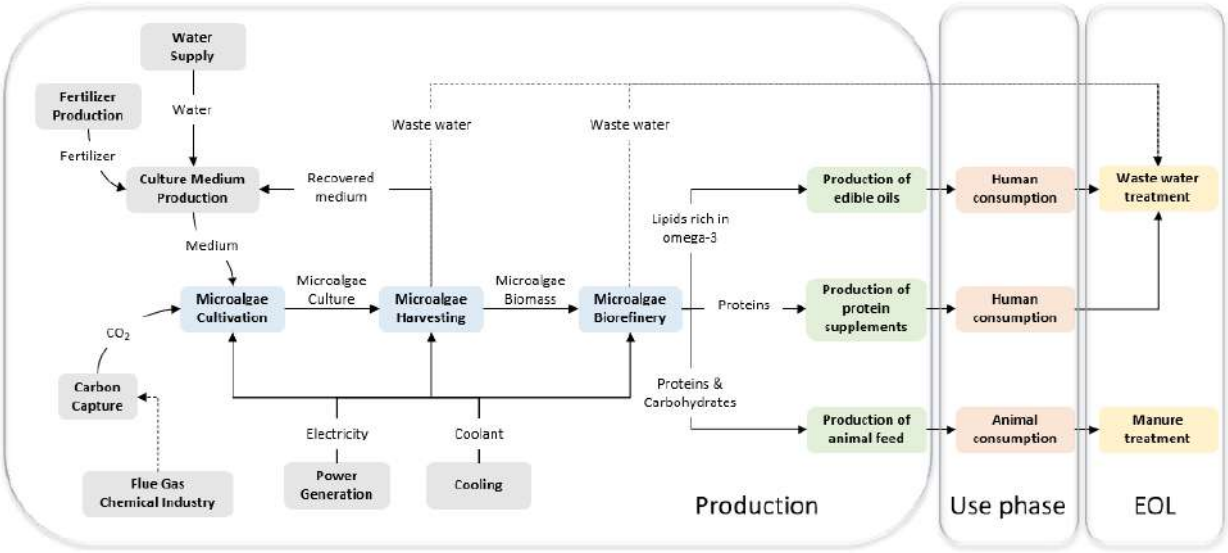

Figure 1. Overview of the microalgae production and biorefining system under study.

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3 Identified sustainability assessment challenges

3.1 Main environmental challenges associated with the sector

The chemical sector ranks as the third largest emitter of greenhouse gases in the European Union (EU), a consequence of its heavy dependence on fossil fuels and non-renewable feedstocks. This significant carbon footprint underscores the urgency of transitioning toward renewable biomass sources (De Souza et al., 2024). Among the promising pathways to address this challenge is the emerging microalgae industry, where microalgal biomass is converted into bio-based products through sustainable biorefinery processes.

However, it is inherently challenging to delineate the principal environmental challenges of the algae sector solely based on the sustainability assessment conducted in this case study, due to the considerable heterogeneity in cultivation and production methodologies across both microalgae and macroalgae systems. Variations in cultivation techniques, ranging from photobioreactors to open ponds, combined with differences in scale, geographic location, strain selection, and input materials, contribute to wide disparities in environmental performance outcomes (Braud et al., 2025).

Moreover, process configurations, resource sourcing, or operational parameters can significantly influence key aspects of the environmental performance, such as energy consumption, nutrient use, and direct greenhouse gas emissions. As such, extrapolating generalizable environmental challenges for the sector necessitates careful contextualization and recognition of this variability.

3.2 Challenges which are not properly addressed

While the microalgae industry holds considerable promise in reducing the chemical sector's environmental burden, several methodological and analytical challenges remain insufficiently addressed when evaluating its true sustainability performance. Assessing the environmental footprint of these bio-based products and respective biorefineries via LCA can be challenging (Tschulkow et al., 2024) because of issues related to: multifunctionality; biogenic and dynamic carbon accounting; modelling of end-of-life, and uncertainty considerations. In that context, the ALIGNED EU project provided a framework of tools and methods for the purpose of overcoming these challenges, while also enabling a high-quality assessment of biobased products.

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4 Recommendations

As a part of the ALIGNED project, A4F developed several targeted recommendations to support companies and consultants in the microalgal sector in improving the quality, consistency, and impact of their sustainability assessments.

These recommendations are grounded in the project's findings and aim to address current methodological challenges. Figure 2 outlines six core recommendations that serve as strategic priorities for advancing robust, transparent, and actionable sustainability practices.

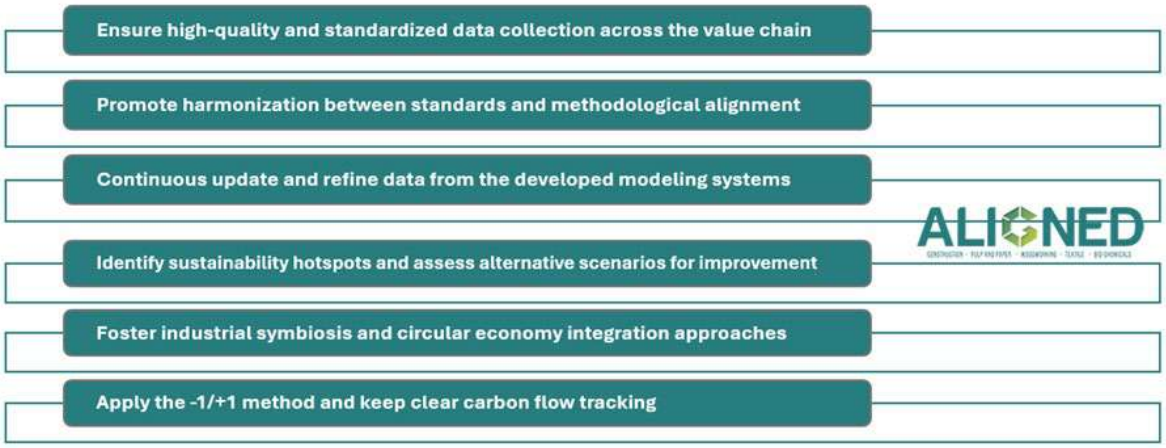

Figure 2. Recommendations for the bio-based sector

Each illustrated recommendation is further elaborated in the sections that follow, providing detailed guidance for implementation, with a specific focus on the microalgae sector, through insights obtained during the development of the ALIGNED project.

4.1 Ensure high-quality and standardized data collection across the value chain

As the microalgae sector continues to grow (Gurreri et al., 2024), the development of comprehensive and standardized sustainability assessment frameworks becomes increasingly important to ensure consistency and comparability across different studies. However, to achieve that, it is necessary to have a strong foundation of high-quality, reliable, and transparent data collection, although there exists a significant lack of high-resolution inventory data (Bradley et al., 2023). Due to that constraint, the recommendation is that companies in the microalgal sector should **prioritize primary data collection from operations under their direct control**. This includes detailed, process-specific information on (1) material and energy use; (2) waste stream outputs; and (3) CO_2 inflows and outflows. **In cases where input data is lacking, secondary data from reputable databases should be utilized when compiling life cycle inventories.** From the insights obtained through ALIGNED, it can be outlined that transparency and traceability are essential for meaningful sustainability performance assessments. Also, data sources should be clearly documented.

The recommendation is also to **use standardized data templates**, such as those developed during the ALIGNED project, to ease data sharing and improve the reproducibility of results. These templates are publicly available for downloading through the Zenodo ALIGNED community repository (Pizzol et al., 2024a).

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4.2 Promote harmonization between standards and methodological alignment

A key recommendation is to **harmonize methodologies across the microalgal sector**. This process is essential to enhance the comparability of sustainability assessments for the different technologies and production processes within the sector.

Since A4F joined the ALIGNED project in 2023, A4F and Aalborg University (AAU) have collaborated on the LCA of a specific microalgae cultivation and biorefinery product system (cf. section 2X). This collaboration helped to align methodological practices, increase transparency, and improve data input quality, while also allowing for the extrapolation of methodological insights useful not only to the company but potentially to other organizations within the microalgal sector. As a result, content produced throughout the ALIGNED project was incorporated into the first white paper of the European Algae Biomass Association (EABA), aimed at serving as a practical and accessible guide for non-LCA experts (Braud et al., 2025). In July 2025, the project coordinator of ALIGNED and participant in Work Package 9 acted as an expert reviewer for the information paper, thereby strengthening the credibility of the guidelines issued for the community and new LCA practitioners.

A second information paper from EABA is currently under development and will be available by December 2025. This paper will be hosted on the Zenodo repository, specifically within the Algae LCA community page, and will be made openly accessible to the public. In the same way as the first paper, it will follow a living-document format, undergoing continuous updates to reflect the latest insights, methodological advances, and developments in the field. ?. This version is intended for LCA practitioners seeking guidance and standardization on more complex and advanced topics. It will cover a broad range of subjects, including methodological challenges, such as the selection of relevant impact categories, and insights into different approaches of LCA analysis, applied to distinct microalgae growth modes (e.g., heterotrophic vs. autotrophic systems).

As part of its development, collaboration is expected once again with AAU, as well as with the Work Package 2 leader from the ALIGNED project, the Institut National des Sciences Appliquées de Toulouse (INSA). Both partners have been proposed to act as expert reviewers, contributing to the scientific robustness of the publication, and once again standardize methodologies for the microalgae sector.

Initiatives like the one promoted by A4F, which facilitated the partnership between the LCA Task Force of the EABA and the ALIGNED project, exemplify effective efforts to standardize and unify approaches within the microalgae sector.

4.3 Continuous update and refine data from the developed modeling systems

Given the evolving nature of databases, market dynamics, and technological innovations, sustainability models derived from case studies must be updated periodically to improve the accuracy of the data used (Dorr et al., 2023). Based on insights from the ALIGNED project, key recommendations include: **(1) clearly specify the version of tools and datasets used; (2) annually check for database updates, to update the version and, consequently, revise the LCA models for the most recent data incorporation; and (3) update or model real operational and region-specific scenarios to better reflect the actual materials, processes, and on-site conditions.**

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Additionally, it is recommended to **perform sensitivity analysis** to evaluate and report the uncertainty related to life cycle modeling and process simulation, as it helps identify key parameters that affect results and supports more robust decision-making. Tutorials and guidelines for conducting this kind of analysis can be found in the Zenodo records. (Pizzol et al., 2024b).

An example derived from the project involves a comparative assessment based on two distinct versions of the ecoinvent database, versions 3.8 and 3.10. This comparison focused on evaluating the variability of life cycle impact data between these versions, with specific attention to the Global Warming Potential (GWP) indicator values associated with the electricity consumption during the cultivation phase of the ALIGNED microalgae case study.

In version 3.8, the dataset labelled as "Electricity, low voltage {PT} | electricity production, photovoltaic, 570 kWp open ground installation, multi-Si" exhibited a GWP impact of 3.51 kg CO_2-eq/kg EPA-rich oil. A detailed and site-specific life cycle modeling of the actual photovoltaic system employed at the A4F facility was conducted, yielding a GWP impact of 3.19 kg CO_2-eq/kg EPA-rich oil. Both of these values are related to the associated impact of the required electricity consumption for the cultivation phase of the microalgae, in order to produce 1kg of EPA-rich oil.

Upon transitioning to version 3.10 of ecoinvent, notable changes in impact values were observed. The same background dataset in the updated version reported a GWP value of 3.70 kg CO_2-eq, while the modeled alternative data presented a corresponding impact of 3.42 kg CO_2-eq. These results represent a 5.41% increase in the GWP of the background database entry and a 7.21% increase regarding the modeled system's impact. This analysis highlights the sensitivity of LCA outcomes to updates in background database inventories and underscores the importance of periodically reassessing environmental impacts due to the evolving nature of data sources.

4.4 Identify sustainability hotspots and assess alternative scenarios for improvement

The identification and analysis of environmental hotspots are essential for enhancing the importance of sustainability assessments. Through those assessments, it is possible to evaluate alternative scenarios that either more accurately reflect real-world system configurations or offer insights into options with reduced environmental burdens.

As previously stated, in the context of microalgae production, however, no standardized guidance or recommendations exist for identifying sustainability hotspots, since systems present a variety of characteristics that make them unique (e.g., operation and type of reactor, or growth modes).

These distinct characteristics can be related to the heterogeneity surrounding a combination of biological, technical, and regional factors. That variability can arise from the type of cultivation systems employed, which may be either open, such as open raceway ponds, or closed like unilayer horizontal tubular photobioreactors (UHT-PBRs). Furthermore, production may take place in onshore or offshore environments. Additional variability can also be obtained from the source of nutrients (e.g., fertilizers or recovered waste streams),

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productivity rates, harvesting techniques, biomass processing methods, and numerous other parameters (Braud et al., 2025).

Since technologies are widely different within the microalgal sector, it cannot be expected that the same hot spots would appear in the LCA. Therefore, it is recommended that **the analysis of hotspots must be conducted carefully, case-by-case**. In the same way, it is recommended that to **evaluate case-specific scenarios of improvements**, this assessment should be informed by the analysis of hot spots.

4.5 Foster industrial symbiosis and circular economy integration approaches

Leveraging industrial and other economic activities through symbiosis is a strategic opportunity for enhancing the overall process sustainability through a circular economy approach (Fussone et al., 2025).

Specifically in the microalgae sector, operations can benefit from proximity to industrial partners by reusing process side streams (e.g., liquid effluent streams or CO_2 both from biogenic or fossil sources) or through the valorization of by-products and biomass fractions, which can contribute to the reduction of costs and environmental impact of the overall process.

In that sense, it is recommended that **companies seek to establish partnerships with nearby industrial facilities to implement systems for the reuse of currently underexploited side-streams,** aiming to reduce both the environmental impact and the operational costs of their processes. Based on the LCA done in ALIGNED and the work with biorefinery cases, the use of the substitution method, and the analysis of constraints to biomass supply, there is, however, an important caveat. It must be further stressed that the established symbiosis results should focus exclusively on the upgrading of currently underexploited side streams of materials and energy. This means that side-stream materials should change from downcycling processes to upcycling ones, resulting in the production of high-value products from low-value ones. In the same way, energy side streams should change from situations of energy loss to energy conservation. Simply redirecting side streams from one valorisation pathway to another does not necessarily lead to an improvement in environmental performance at the whole-system level.

4.6 Apply the -1/+1 method and keep clear carbon flow tracking

Given the methodological complexity encountered during the ALIGNED project, with the application of substitution approaches and the integration of background datasets, **it is recommended that future works prioritize a comprehensive analysis of carbon flows across both foreground and background data**. As a foundational step, **it is recommended that the microalgal sector adopt the -1/+1 biogenic carbon accounting approach for biogenic CO_2 flows**, as it enables consistent comparisons between fossil-based and bio-based products and supports transparent, informed decision-making across the value chain.

In this method, the emission of 1 kg of CO_2, whether fossil or biogenic, is assigned with a GWP value of +1 kg CO_2-eq in the impact assessment phase. Conversely, in the inventory phase removing 1 kg of CO_2 from the atmosphere, such as through biomass growth, is assigned a negative value of (e.g., –1 kg CO_2), reflecting a negative emission (Hamelin et al., 2024).

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Complex industrial symbiosis situations can be effectively modelled using this approach by appropriately setting the system boundaries of the LCA study. For example, let's consider the case of CO_2 obtained from a nearby industrial facility, as a by-product. The emission of this CO_2 is momentarily avoided and thus gives a credit for the microalgae production system (negative emission: carbon uptake). The microalgae production system will however carry the burdens associated with processes of CO_2 capture, purification and transportation. At the same time however, it will lower the overall system burden by reducing the need for alternative CO_2 sources, which also carry a burden associated with their production. The CO_2 taken up by the microalgae becomes biomass with carbon content, and ultimately such carbon is oxidised and released as CO_2 at end of life thus closing the cycle (positive emission: carbon release).

As recommended by the ALIGNED project, for this approach to be effective, the LCA should be conducted using a cradle-to-grave scope, which means that the end-of-life of the biobased products should be included within the system boundary. This is important to avoid misleading claims of "carbon negative" biobased products that are the result of a model where release at the end of life is excluded from the scope. Since end-of-life cannot always be anticipated accurately, it is recommended to include different scenarios, including full-oxidation of the carbon content of the biobased product, in order to close its carbon balance over the life cycle.

To support this accounting approach, it is crucial to distinguish and report biogenic and non-biogenic elementary flows during the Life Cycle Inventory (LCI) phase, with particular attention to carbon flows. Although it does not directly affect the Life Cycle Impact Assessment (LCIA), it is vital for ensuring a transparent and comprehensive interpretation of climate change impact results. Further, attention must be directed toward ensuring alignment between carbon accounting principles and the treatment of carbon flows in background datasets, such as those provided by the ecoinvent database. Inconsistencies in how carbon is represented (e.g., emissions to air instead of inputs from nature) can lead to double counting and contribute to a reduction in the reliability of results.

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5 Conclusions

Extrapolating from the insights gained by applying the ALIGNED methodologies in the case study on microalgal production exploited by A4F, this document aims to provide recommendations relevant to the whole microalgal sector.

Six specific recommendations have been proposed. It is specifically recommended to: 1) Ensure high-quality and standardized data collection across the value chain, 2) Promote harmonization between standards and methodological alignment, 3) Continuously update and refine data from the developed modeling systems, 4) Identify sustainability hotspots and assess alternative scenarios for improvement, 5) Foster industrial symbiosis and circular economy integration approaches, and 6) Apply the -1/+1 method to keep a clear carbon flow tracking.

The expectation is that different stakeholders might be the target audience for these recommendations. Specifically, technology developers and industry players should focus on improving the data quality and availability, as well as updating such data. LCA analysts working with microalgal technologies should focus on the case-specific identification of hotspots and the correct application of carbon accounting methods. Sectoral organizations and policy makers should focus instead on improving methodological harmonization and pushing for clear guidance on carbon tracking, ideally using methods selected in the ALIGNED project.

The proposed recommendations are not exhaustive, but yet intended to support the microalgal sector in improving the environmental performance, based on efforts from multiple stakeholders.

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