# Algae based biorefineries: boon or bane?

## Lessons learnt from a decade of research and demonstration units worldwide [1]

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## 1. Introduction

Algae cultivation has raised high hopes for a sustainable production of various bio-based products such as biofuels, phytonutrients or bio-chemicals from seemingly abundant sunlight and $CO_2$. However, cultivation in sufficient concentrations, harvesting and conversion into products, especially via biorefineries, require technological solutions that can have considerable impacts on sustainability, namely environment, economy and society.

Development and diversity of algae based products produced in biorefineries have increased tremendously in the last decade, especially in the research and demonstration levels as most of them are not yet economically viable. To identify their impacts on sustainability and optimize their sustainability, many life cycle assessments (LCA) and/or sustainability assessments have been performed and published in expertises, journals and conference papers (such as [1], [2]). From these publications many lessons can be learned.

## 2. Methodological approach

The overall sustainability assessment is based on a life cycle approach, which takes into account the entire life cycle from "cradle" (= algae cultivation) to "grave" (= e.g. end-of-life treatment) including the use of co-products, see Figure 1.

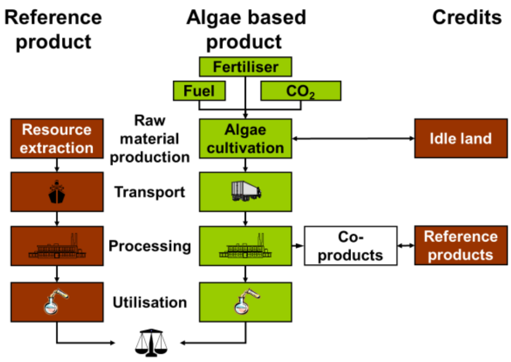


**Figure 1:** Schematic illustration of the life cycle comparison of an algae based product (green) with conventional reference products such as dietary supplements or chemicals (brown).

[1] Citation: G. A. Reinhardt, M. Hemmen: Algae based biorefineries: boon or bane? Lessons learnt from a decade of research and demonstration units worldwide. Keynote talk. In: Proceedings of the 5$^{th}$ Latin American Congress on Biorefineries, January 7-9, 2019, Concepción, Chile, p19f

If algae are not sold as a whole but processed into a multi-product portfolio, biorefineries are needed for the algae conversion. The algae-based product portfolio can include products such as phytonutrients, feed, biofuels, bio-based chemicals, biomaterials etc. The portfolio varies significantly depending on the algae strain processed and biorefinery concept applied. For an example see Figure 2.

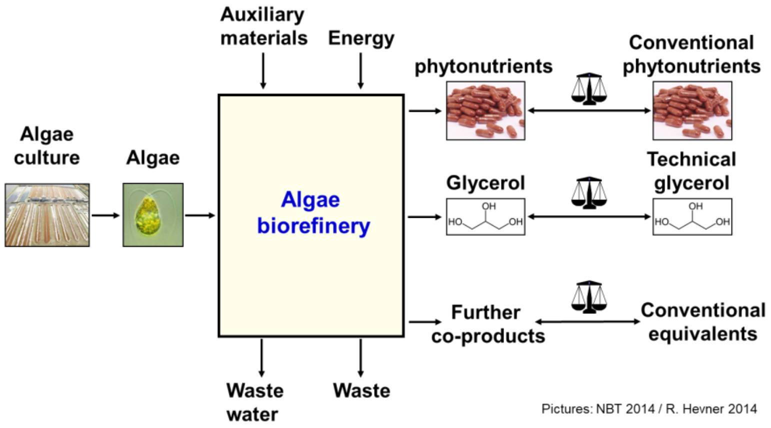


**Figure 2:** Schematic overview of a life cycle comparison of algae-based products from a biorefinery compared to conventional products.

The analysis of the life cycle comparisons follows the so-called integrated life cycle sustainability assessment (ILCSA) methodology (Figure 3) [3], which joins and connects results on individual sustainability aspects to give an integrated view on sustainability concepts. The underlying methodology builds mainly upon existing frameworks. It is based on international standards such as [4] [5], the International Reference Life Cycle Data System (ILCD) guidelines [6], the SETAC code of practice for life cycle costing [7] and the UNEP/SETAC guidelines for social life cycle assessment [8]. ILCSA extends them with features for ex-ante assessments such as the identification of implementation barriers that increase the value for decision makers. This flexibility allows for focussing on those sustainability aspects relevant in the respective decision situation using the best available methodology for assessing each aspect within the overarching ILCSA. Furthermore, it introduces a structured discussion of results to derive concrete conclusions and recommendations. This includes a benchmarking procedure in which all scenarios are compared to a selected benchmark scenario. For a practical application see e.g. [9].

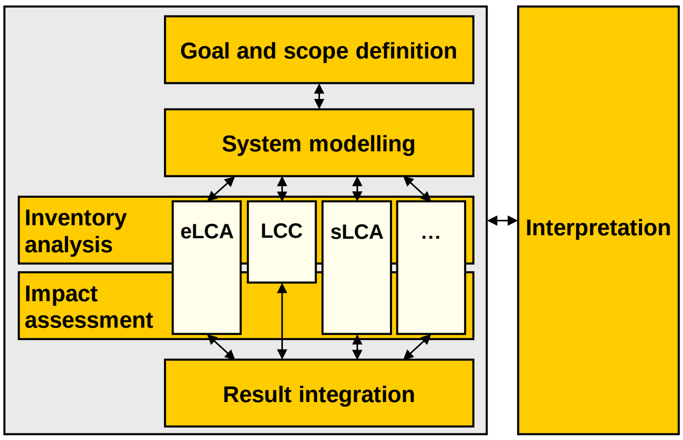


**Figure 3:** Schematic workflow of an integrated life cycle sustainability assessment (ILCSA) [3]. It provides a framework to integrate several life cycle based assessments such as (environmental) life cycle

assessment, (e)LCA, life cycle costing, LCC, social life cycle assessment, sLCA and analyses of other sustainability-relevant aspects.

## 3. Selected results and discussion

To provide a brief insight into the sustainability of algae based products from biorefineries, this chapter contains selected assessment results.

### 3.1. Life cycle assessment

Life cycle assessments (LCAs) help to identify the environmental impacts of products. By changing the respective boundary conditions, the LCA outcomes can change drastically.

Applied to the production of algae based biodiesel, this means that depending on the biorefinery itself and the product system, the manufactured products can vary significantly. To demonstrate this dependency and to point out possible potentials of algae based biodiesel from biorefineries, the extent of different environmental impacts for typical and optimized biodiesel production conditions is exemplarily presented in the following.

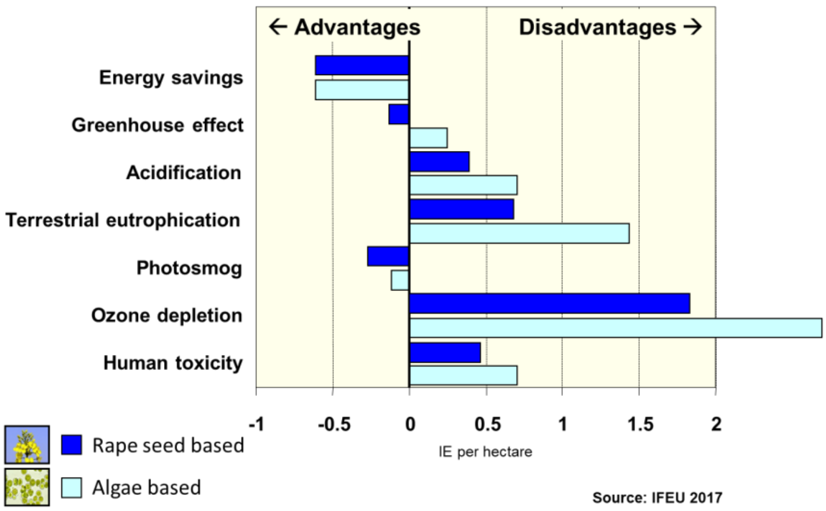


**Figure 4:** LCA results for rape seed based and algae based biodiesel under typical current conditions.

Figure 4 shows the advantages and disadvantages of algae based biodiesel from biorefineries compared to rape seed based biodiesel for a scenario representing typical current technology.

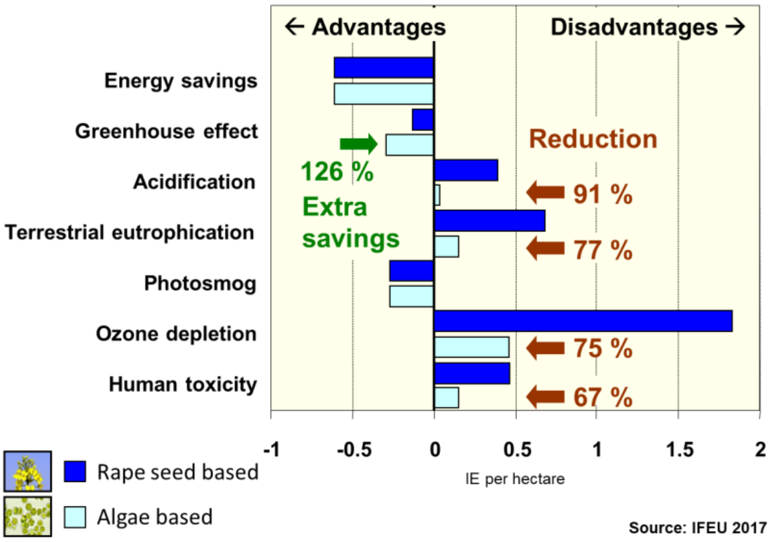


**Figure 5:** LCA results for rape seed based and algae based biodiesel with optimized technology.

In contrast, Figure 5 illustrates the results for an optimised scenario representing the potential technology of tomorrow.

The LCA results show that the optimization of algae cultivation and processing can lead to a much better performance of an algae based product by increasing its environmental benefits and reducing its environmental burdens and that these optimizations are required in order to ensure a better performance than competing products.

### 3.2. Integrated life cycle sustainability assessment (ILCSA)

In the last years, LCA has been extended towards the concept of life cycle sustainability assessment (LCSA) in order to cover not only environmental aspects but also further sustainability aspects. The ILCSA methodology implements this concept in a practicable way. It combines assessments of different sustainability aspects by joining and connecting the different impacts to give an integrated view on the sustainability of products.

Table 1 exemplarily shows results for indicators and algae biorefinery scenarios for the provision of the phytonutrient 9-cis β-carotene and several co-products. The front-runner scenarios, which perform best regarding certain groups of indicators, are [9]:

- Scenario 1 (initial configuration): The realisation and operation of an algae-based biorefinery according to this concept will face least technical barriers.
- Scenario 5 (shorter downstream processing): If this scenario can be implemented as expected, it will be the most profitable option and will pose least potential social risks.
- Scenario 6 (no separation of phytonutrients): If this scenario is realised and the performance expected under optimistic boundary conditions can be achieved, lowest environmental impacts can be reached.

Scenario 1 scores best regarding the technological indicators *maturity*, *vulnerability*, *complexity* and *biological risk*. This reflects that the simplest technology is used, which can be planned, installed and operated facing least challenges. Some of the most important drawbacks of this scenario are: First, the required high effort to overcome technical barriers as e.g. regulatory challenges caused by the management of big amounts of wastewater. Second, high environmental impacts. And last but not least the very low internal rate of return. [9]

**Table 1:** Overview of results for life cycle sustainability assessment of different scenarios for the provision of the phytonutrient 9-cis β-carotene from Dunaliella algae. Impacts that can be avoided by using co-products instead of their conventional alternatives have been subtracted. N/D: no data, N/A: not applicable [9].

| | | | Optimistic performance | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | D-Factory scenarios | | | | | |
| | Indicator | Unit | Scenario 1 Initial configuration | Scenario 2 Membrane pre-concentration | Scenario 3 Whole cell harvesting | Scenario 4 Glycerol recovery | Scenario 5 (shorter down-stream pro-cessing) | Scenario 6 (no carotenoid separation) |
| Technology | Maturity | - | 7.4 | 7.3 | 7.0 | 6.9 | N/D | N/D |
| | Legislative framework and bureaucratic hurdles | - | 6.7 | 6.7 | 7.1 | 7.4 | N/D | N/D |
| | Availability of competent support systems | - | 7.4 | 7.6 | 7.3 | 7.4 | N/D | N/D |
| | Vulnerability | - | 7.1 | 6.9 | 6.4 | 6.2 | N/D | N/D |
| | Complexity | - | 7.0 | 6.8 | 6.3 | 6.0 | N/D | N/D |
| | Biological risk | - | 7.5 | 6.7 | 5.3 | 5.3 | N/D | N/D |
| | Technological risk: Hazardous substances | - | 5.8 | 5.8 | 5.8 | 5.9 | N/D | N/D |
| | Technological risk: Explosions and fires | - | 7.4 | 7.4 | 7.4 | 7.5 | N/D | N/D |
| Environment | Global warming | t $CO_2$ eq. / kg 9-cis β-c. | 14 | 12 | 15 | 15 | 2 | 0.2 |
| | Energy resources | GJ / kg 9-cis β-c. | 250 | 216 | 271 | 265 | 30 | 4 |
| | Acidification | kg $SO_2$ eq. / kg 9-cis β-c. | 64 | 58 | 71 | 71 | 3 | 1 |
| | Eutrophication | kg $PO_4$ eq. / kg 9-cis β-c. | 2.8 | 2.4 | 3.0 | 3.0 | 0.1 | 0.1 |
| | Photochemical smog | kg ethene eq. / kg 9-cis β-c. | 6 | 6 | 7 | 7 | 3 | 0.1 |
| | Ozone depletion | g CFC-11 eq. / kg 9-cis β-c. | 7 | 6 | 7 | 7 | -2 | 1 |
| | Human toxicity (respiratory inorganics) | kg PM10 eq. / kg 9-cis β-c. | 62 | 49 | 60 | 59 | 4 | 1 |
| | Freshwater use (global) | $m^3$ / kg 9-cis β-c. | 114 | -104 | -133 | -133 | -126 | 8 |
| | Water (local) | - | - | 0 | 0 | 0 | 0 | 0 |
| | Soil | - | 0 | + | + | + | + | + |
| | Fauna | - | 0 | + | + | + | + | + |
| | Flora | - | 0 | + | + | + | + | + |
| | Landscape | - | + | + | + | + | + | + |
| Economy | Operating Expenditure | Million €/year | 27 | 20 | 29 | 29 | 20 | 4 |
| | Total Revenue | Million €/year | 33 | 33 | 41 | 41 | 34 | 4 |
| | Gross Margin | % | 21% | 41% | 29% | 29% | 41% | 11% |
| | Capital Expenditure | Million € | 51 | 52 | 53 | 53 | 4 | 4 |
| | Economic Internal Rate of Return (10 years) | % | 3% | 20% | 15% | 15% | 296% | N/A |
| | Net Present Value (10 years, 5% discount) | Million € | 46 | 111 | 91 | 93 | 124 | -15 |
| Society | Labor rights and decent work | Risk of negative impact/ g 9-cis β-carotene | -91 | -107 | -45 | -53 | -107 | -16 |
| | Health and safety | | -24 | -35 | 2 | 4 | -23 | 0 |
| | Human rights | | -22 | -38 | 0 | -11 | -96 | -17 |
| | Governance | | 43 | 23 | 46 | 33 | -16 | -3 |
| | Community infrastructure | | -94 | -106 | -54 | -60 | -110 | -13 |

## 4. Conclusions and recommendations

Based on the LCA and ILCSA results of many publications on algae based products from biorefineries, following lessons learnt can be summarised:

- **Not all algae-based products are sustainable:** Algae-based products are not sustainable just because they are "bio". There is a remarkable potential for sustainable algae-based products, but they must be developed in accordance with all sustainability criteria and in accordance with other goals towards a sustainable development including the UN Sustainable Development Goals.

- **Site selection for algae cultivation is crucial:** Arable land should not be used (exceptions subject to conditions). Furthermore, sufficient availability of freshwater should be guaranteed, also if saltwater algae are cultivated. Additionally, rural communities should be favoured to increase social benefits and reduce costs of land. Even in Europe many regions are suitable for algae cultivation – if heating can be avoided or provided with very low impacts e.g. from waste heat or geothermal. Finally, specific requirements of cultivated algae strains should be taken into account.
- **$CO_2$ with no or little impacts is required:** E.g. flue gas from a power plant, cement factory or steelworks. Still, an extension of the service life time of e.g. fossil power plants for algae cultivation is not justified.
- **Solar power can reduce impacts decisively:** Use as much of your own renewable energy as possible for algae cultivation. 80% PV power supply is possible with only 15% to 50% additional land occupation.
- **Social risks and environmental performance in the value chain need to be managed:** High social risks are not a no-go but entail obligations. E.g. the situation should be closely monitored to avoid negative social impacts and suppliers according to social and environmental reporting standards such as GRI or EMAS should be selected.
- **Co-product production can make some money and enormously improve land use related environmental burdens:** Options to produce co-products have to be investigated. All algae constituents should be converted to value-added products. And also, the potential of using some biomass streams as feed or even replace animal-based ingredients e.g. in novel foods should be examined.
- **Policy conditions are important for sustainability**: Algae based products from biorefineries are not yet competitive in most cases. Therefore, the development of technologies and market introduction for such algae based products with a high positive impact on sustainable development should be supported. Furthermore, in the future, solar power may compete for land and CCU/CCS may compete for remaining $CO_2$ sources. Hence, a coordination of policies is required. Both policymakers and consumers can and have to contribute to sustainability, too
- **Algae cultivation and processing requires high expenditures. Thus, improvement is necessary:** Many involved processes still have a substantial potential and need for optimisation – as for any truly innovative technology. Comprehensive life cycle sustainability assessment helps to identify these processes and suitable measures.

## 5. Acknowledgements

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