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REVIEW OF THE LCA ELEMENTS APPLYING TO THE MICROALGAE LIPID EXTRACTION

Carmen Gabriela CONSTANTIN[1], Burçin ATILGAN TÜRKMEN[2], Aurora DOBRIN[1], Ion CERTAN[1]

[1]Research Center for Studies of Food Quality and Agricultural Products, University of Agronomic Sciences and Veterinary Medicine of Bucharest, 59 Mărăști Blvd, District 1, 011464, Bucharest, Romania
[2]Department of Chemical Engineering, Bilecik Şeyh Edebali University, 11011, Bilecik, Turkey

Corresponding author email: certan.ion@qlab.usamv.ro

Abstract

Although significant studies of microalgae have been published, there is no clear information regarding the advantages, challenges, or feasibility of polyunsaturated fatty acids (PUFA) production in a sustainable large-scale process. Such information on the current state of PUFA extraction applied to feed and food is particularly important for researchers and stakeholders to identify and apply the most sustainable technology. Based on highly cited academic articles and other digital libraries of academic journals, this study aims to provide a comparison between different microalgae lipid extraction methods through LCA parameters evaluation. PUFA extraction from microalgae Nannochloropsis sp. used as feedstock, is evaluated using methods such as ultrasound, microwave, supercritical fluid extraction, and accelerated solvent extraction in a comprehensive review. Extraction yield, nature of the extraction solvent, energy type source and consumption, labour, and extraction time influenced the specific LCA parameters, quantified for global warming potential, ecotoxicity potential, fossil resource scarcity, and cumulative energy demand. It is possible to reduce production costs and environmental impact by selecting the appropriate method and optimizing these parameters.

Key words: *life cycle assessment, global warming potential, fossil resource scarcity, cumulative energy demand, sustainability.*

INTRODUCTION

Nowadays, in marine ecosystems factors such as overfishing and resource depletion are considered threats. Therefore, there is a need to find and develop such methodologies to identify, quantify, and assess the main indicators related to marine biodiversity in order to maintain sustainable development.

Currently, fish and meat are the main sources of Polyunsaturated Fatty Acids (PUFAs), whereby meat causes high environmental impact, and fish catch cannot meet the demand of eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) (Schade et al., 2020). PUFAs are components of cell membrane phospholipids serving as precursors for hormone-like inflammatory mediators. These long-chain acids are crucial for the health of humans and most animals, because they do not have the ability to produce them, so it is important that they are supplemented in the diet. This is why the demand for EPA and DHA has significantly increased (Sá et al., 2020; Togarcheti et al., 2021). It seems like the long chain PUFA are involved in regulation of cell metabolism at the nuclear level being related with the progression of chronic diseases. Scarcity in saturated acids is associated with the blood lipid profile (Shi et al., 2018).

However, the long-chain n-3 PUFAs, EPA, and DHA, are scarce nutrients in a global context. Therefore, a valuable renewable source of PUFAs may be represented by microalgae. Nannochloropsis sp. microalgae are easily grown at upscale conditions and can be used to synthesize high-value compounds for the pharmaceutical, cosmetic, and nutraceutical industries (Gaber et al., 2021; Ferreira et al., 2013). Due to the of the cell's structural properties, the identification of the proper solvent, and extraction technology for its components such as lipids remains the main challenge (Ferreira et al., 2013). It is critical to increase lipid productivity in order to improve the process's economic competitiveness. This can be achieved by reducing the high energy requirements associated with water management and lipid extraction from the biomass. Producing and quantifying fatty acids is a laborious and time-consuming process that includes several steps such as extraction, fractionation, methylation, and quantification. Furthermore, the process is not environmentally friendly because it uses various organic solvents in this step. It is vital to look into alternate lipid extraction techniques in order to make the process more environmentally friendly. These methods should be cost-effective and requiring less time and energy while ensuring high yields of fatty acids. This reduces the environmental impact of the process and makes it more sustainable (Sá et al., 2020).

In this context, a comprehensive accounting of the environmental sustainability assessment is required. Life Cycle Assessment (LCA) is an important tool for determining the most environmentally friendly process (Togarcheti et al., 2021; Barahmand et al., 2022).

Although the LCA is highly valued, the number of LCAs on PUFA products (Van Boxtel et al., 2015) produced by *Nannochloropsis* sp. is scarce, most of the studies being related to biomass production and biofuels obtaining (González-Delgado and Kafarov, 2011). Throughout time, the LCA and sustainability assessment was applied for the entire algal biodiesel processes. (ref) The LCA of algal biodiesel production process provided a quantitative measure for its sustainability. Even though the published LCA studies of algae biodiesel processes are reviewed, demonstrates that there are few comprehensive studies that cover the complete process. Therefore, the outcomes can be inconclusive. The variability of algal species, reactor type and conditions, and other factors influence the LCA outcomes. Also, on LCAs applied to the algae biodiesel process, a lack of systematic influence on the outcomes.

In recent decades, scientists have been concerned with balancing the costs of their findings with their long-term viability in order to develop renewable-energy-based products. Therefore, clear and standardized frameworks are necessary for the economic sustainability. The techno-economic analysis (TEA) and the life cycle cost analysis (LCCA) are two widespread methodologies to calculate the economic indicators. According to Giacomella (2021), the TEA's methodological steps may be related to the following steps: (a) technology readiness levels (TRL), (b) elements and boundaries, (c) market conditions, costs, and feasibility, (d) profitability, (f) risks and uncertainty, and (g) recommendations. Therefore, TEA's methodological steps comprise (1) problem definition and objectives, (2) cost analysis, (3) discounting future cash flows and economic evaluation, (4) considering risks and uncertainties, and (5) comparing the alternatives and possibilities.

Although the use of TEA is increasing, it is very difficult to define what TEA constitutes. However, researchers have defined the methodology, meaning that there are three key questions related to the mechanism and the profit of the technology, and whether the technology is desirable.

Despite their widespread acceptance, guidelines and comprehensive documentation on their features are limited (Barahmand et al., 2022). Therefore, based on the published scientific articles the aim of this study is to identify the main LCA system insights into the challenges of PUFA. The data will be adapted and applied to extraction techniques with Nannochloropsis sp. serving as a matrix.

LIFE CYCLE ASSESSMENT (LCA)

LCA is a tool used in environmental management to determine the material, energy, and waste flows and their potential impacts on the environment over the course of a process, product, or service. The evaluation covers the entire life cycle, including raw material extraction and processing, production, transportation, and distribution, use, re-use, maintenance, recycling, and final disposal (Muralikrishna & Manickam, 2017).

The International Organization for Standardization (ISO) established the ISO 14040 and ISO 14044 standards (ISO, 2006a, 2006b), which define the LCA methodology. As shown in Figure 1, LCA is composed of four interconnected steps based on this set of standards. These include impact assessment, inventory analysis, goal and scope definition, and result interpretation.

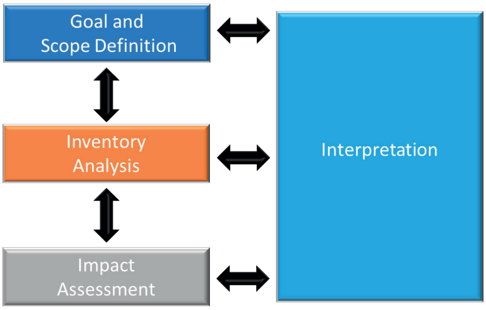

Figure 1. Life cycle assessment framework

The product system is defined in terms of the study's system boundaries and a functional unit during the goal and scope defining stage. For the purpose of comparing alternative products or services, the functional unit is crucial. The life cycle inventory (LCI) analysis stage is used to estimate the amount of resources consumed, waste produced, emissions, and other factors associated with each stage of a product's life cycle. The flows of energy and materials between stages of a life cycle are modelled. For each functional unit, the overall models offer mass and energy balances for the product system, including all of its inputs and outputs into the environment (Azapagic, 2010; Pennington & Rydberg, 2005). The potential environmental impacts resulting from the elementary flows (environmental resources and releases) obtained in the LCI are evaluated in the impact analysis (LCIA) stage. First, the environmental impact categories relevant to the study are chosen and defined, and the environmental impacts are calculated by multiplying the inventory items by the relevant coefficients (Guinée et al., 2011). Environmental impacts including emissions, energy, carbon, water, toxicity, ozone depletion, eutrophication, acidification and resource depletion are impact categories commonly assessed in LCA studies. Different impact assessment methods such as TRACI, Ecoindicator, ReCiPe and CML methods. Selected environmental impact categories are presented as an example in Figure 2. The final step involves a thorough analysis of the data to identify the major environmental impact categories and impact hotspots. It is then possible to use these to suggest ways to improve (Azapagic, 2010).

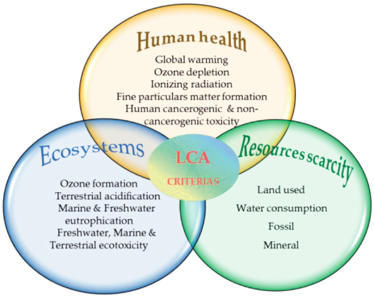

Figure 2. Environmental impact categories based on ReCiPe impact assessment method

LIFE CYCLE ASSESMENT OF LIPID EXTRACTION FROM MICROALGAE

This paper provides a thorough comparison of the environmental sustainability of various microalgae lipid extraction methods. For these purposes, studies on life cycle assessment found in the literature have been reviewed. Using "LCA parameters on microalgae PUFA extraction" as searching words, on Science Direct were only 166 results from 2005. The highest number of 37 articles related to the key words were found in 2022 (Figure 3). When the studies in the literature are examined, it is discovered that they differ in terms of scope, purpose, target, and techniques used. This section of the paper reviews and analyses LCA studies using the LCA methodology.

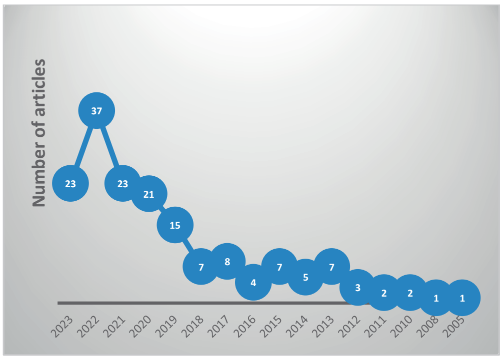

Figure 3. Number of articles in Science direct platform related with LCA parameters and microalgae PUFA extraction

1. *Goal and scope definition*

The aim of the study, the product or process system in terms of the system boundaries, and a functional unit are all described in the goal and scope definition of an LCA. The reviewed studies have different goal and scope The reviewed LCA studies' functional units vary based on the goals and parameters of the research.

Bartek et al. (2021) aims to investigate and compare the environmental impact of docosahexaenoic acid (DHA) produced from algae with substrate derived from dark fermentation (DF) using food waste to that of DHA produced from Peruvian anchovy oil. The functional unit used was selected as 1 kg of lipids (neutral and free fatty acid). At this point, three lipid extraction scenarios were described: CHCl3-MeOH, CO_2 expanded methanol, and non-expanded methanol.

Comparing the environmental effects of various Nannochloropsis sp. and P.tricornutum cultivation scenarios with aquaculture and capture fish production as conventional sources of EPA and DHA is the goal of the another study (Schade et al., 2020). In study, as the functional units was kg DM (dry mass) for microalgae and 1 kg of fresh fish fillet, for protein 50 g and 500 mg EPA+DHA, corresponding with daily intake recommendations per person (World Health Organization).

In their research, Medeiros et al., (2022) quantify the energy demand, economic sustainability, and global warming potential of microalgae biomass production. The product system consists of carbon dioxide-injected open raceway ponds for microalgae cultivation, followed by settling, filtration, and centrifugation for harvesting. A kilogram of microalgae biomass production in total solids with 80% moisture has been used in the evaluated scenarios.

Paramita (2012) in his thesis analysed the modelling of extraction processes (hexane extractions and supercritical fluid extraction CO_2. Also, in this case the basis for inventory 1 kg of oil in the algae biomass was used to analyse efficiency, effectiveness and environmental impact.

Shi et al. (2018) investigated the environmental impacts of different harvesting and extraction technologies. The gate-to-gate system boundaries are chosen. In the study, two different functional units were chosen. The functional unit for harvesting technologies was determined as 1 kg of dry algae biomass harvested, while the functional unit for extraction technologies was determined as 1 MJ lipid oil output.

Also, Papadaki et al. (2016) aims to evaluate the environmental sustainability linked to various extraction techniques for astaxanthin recovery. Using microwaves and ultrasonics, a comparative study was conducted between traditional solvent extraction and novel green extraction techniques to recover bioactive compounds, particularly astaxanthin, from Haematococcus pluvialis microalgae. A life cycle assessment, encompassing the cultivation, harvesting, and extraction treatment up to the production of extracts rich in astaxanthin, was carried out. The functional unit was defined as 1 kg equivalent (eq.) of astaxanthin recovered from *H. pluvialis* to be used as an additive in cosmetics and nutraceutical applications.

Through process simulation, Lopes et al., (2023) developed the conceptual design of a microalgae production plant, as well as its harvesting, dewatering, cell disruption, and aqueous fraction processes. The functional unit was defined as 1 kg of ash-free dry-weight biomass produced and processed in the system.

2. *Life cycle inventory*

According to the literature, there are several aspects that should be considered for the inventory analysis stage.

LCI applied in microalgae production:

- LCA system boundaries of upscaled total fatty acid (TFA) production (Gaber et al., 2022; Schade et al., 2020);
- Scheme of energy inputs (Ferreira et al., 2013);
- Flowchart of microalgae production and processing into various fractions of interest (Lopes et al., 2023; Zi Hao et al., 2023);
- Influence of the life cycle stages on the environment parameters (Medeiros et al., 2022).

According to Medeiros et al. (2022), the following variables were used in the analysis for cultivation and harvesting:

- Input: occupied area, water, saline, infrastructure (concrete, polypropylene, excavation, steel, PVC, pipe, cast iron, CO_2), synthetic fertilizer), transport of fertilizer, truck, electricity, labor.

- Output: water, air, CO_2 loss, air, water, blowdown effluent, biomass-loss.

For energy demand, carbon footprint and financial cost contributions of microalgae biomass production the following contribution groups were analyzed: cumulative energy demand (CED), global warming potential (GWP) and capital and operational cost Medeiros et al. (2022).

Lopes et al. (2023), in their work, created a process model that can simulate an industrial plant to estimate mass and energy balances, optimize scheduling, and calculate production costs for a large-scale plant. They also combined TEA and LCA, like Medeiros et al. (2022). In their study, four scenarios and three microalgae strains (*Nannochloropsis* sp., *Dunaliella* sp. and *Spirulina* sp.) were considered. In the scenarios, they analyzed the following parameters: water recirculation, no water recirculation, industrial gaseous CO_2 as a carbon source and flue gas as a carbon source. Each scenario was applied to each microalgae.

Two scenarios are chosen for analysis in the study conducted by Bartek et al. (2021): the conventional fish scenario, in which DHA is obtained from Peruvian anchovy, and the conceptual algae scenario, in which DHA is produced from C. cohnii microalgae using volatile fatty acids (VFA) derived from DF with food waste. The energy used for building construction, processing, end-of-life, and transportation of necessary inputs is included in the system boundary calculation.

Ferreira et al. (2013) analyzed energy inputs and CO_2 emissions for the microalgae culture and downstream processing comparing two methods of oil extraction: supercritical fluid extraction (SFE) and Soxhlet extraction (SE) for bioH2 production. They used as inputs: nutrients (N, K, P, Fe, Na, B, Mn, Zn, Co), deionized water, light intensity, centrifugation, drying, cutting mill and ball mill, fermentation, sterilization, drying and evaporation.

Gaber et al. (2022) considered for LCA analysis two systems upstream (algae cultivation and harvest with centrifuges) and downstream (cell disruption using homogenization, the extraction of TFA, biodiesel production, and solvent vaporization) to obtain the final TFA product. In LCI four extraction methods were used: ultrasound, microwave, supercritical fluid extraction, and accelerated solvent extraction, being very important to identify the wide range of parameters and to perform a comprehensive analysis. Therefore, the following parameters were analyzed:

- Pilot reactor and 20-ha upscaled plants:
- Electricity consumption (skid electricity, harvesting electricity, seawater recycling, TFA extraction via solvent and 3-phase separator, cell homogenizer, solvent vaporization);
- Demand of nutrients (sodium nitrate, sodium phosphate, ferric chloride).
- CO_2, cleaning materials and solvents as operational materials;
- Sodium hypochlorite, hydrogen chloride, TFA extraction via solvent and 3-phase separator, cell homogenizer oil, land use),
- Water consumption (cooling water for chiller, cleaning water, cell homogenizer water).

LCI applied in fish feed production and fish growing consider three main costs:

- Energy for feed production, and fish growing in Recirculating Aquaculture System (RAS) (Schade et al., 2020);
- Investment in infrastructure for fish growing;
- Water consumption in RAS (Schade et al., 2020).

3. *Impact assessment*

For the environmental impact study, Restuccia et al. (2022) used SimaPro software, midpoint ReCiPe 2016 (H). This methodology was chosen and preferred over other calculation methods such as ILCD 2011, CML 2001 or TRACI because of the availability of eighteen impact categories (compared to 16 from ILCD 2011 Midpoint, 15 from IMPACT 2002+, 11 from CML-IA Baseline, and 9 from TRACI).

For impact assessment, Gaber et al. (2022) in their study mentioned OpenLCA version 1.7 software with unit processes selected from the LCA database Ecoinvent 3.4 in accordance to ISO 14040/44. The same ISO was also used by Ferreira et al. (2013), Papadaki et al. (2016), Lopes et al. (2023) and ILCD Midpoint 2011 impact assessment method, developed and promoted by the Joint Research Council (JRC) of European Commission, being a very useful tool in order to evaluate fatty acids extraction from microalgae. It included the following aspects: climate change, particulate matter formation, freshwater eutrophication, mineral resource depletion, water resource depletion, and land use. Medeiros et al. (2022) used openLCA v.1.11.0 with the Ecoinvent v.3.6 and TEA method was used for the economic performance. LCA and TEA were integrated for the same goal, scope and foreground inventory.

Into the description of result aggregation were presented the following categories: processes (electricity flows, infrastructure flows, nutrient flows, tap water flows), LCA phases (cultivation, hydrothermal liquefaction and downstream parameters). Togarcheti et al. conducted a study in 2021 that used inventory data from the literature to predict the primary energy demand and environmental impacts associated with unit operations for the production of EPA+DHA from microalgae, and the characterisation methods used were ReCiPe 2016 Midpoint (H) v1.06 and the single-issue method of CED v1.11. In the environmental impact was assessed the following parameters: abiotic depletion potential (ADP), eutrophication potential (EP), GWP and acidification potential (AP). Schade et al., (2020) compared different cultivation scenarios of *Nannochloropsis* sp. and *P. tricornutum* with the production of aquaculture and capture fish as traditional sources of EPA and DHA, using Ecoinvent database v3.4. The following impact categories are used in the analysis: ADP, GWP, Ozone Depletion Potential (ODP), Human Toxicity Potential (HTP), AP, EP, Photochemical Oxidation Potential (POCP), Terrestrial Ecotoxicity Potential (TETP), Marine Aquatic Ecotoxicity Potential (MAETP) and Fresh Water Aquatic Ecotoxicity Potential (FAETP).

Lopes et al., (2023) used SimaPro v9.4.0.1 with the Ecoinvent database v.3.8 and by applying the environmental footprint impact assessment method (EF 3.0). A Monte Carlo simulation was also performed to estimate the possible outcomes of an uncertainty. The environmental impact distribution (%) per sub-system and for each scenario, as well as the environmental impacts for each strain for the scenarios under consideration, were analysed. The following impact categories has been analysed: climate change; ozone depletion; ionizing radiation; photochemical ozone formation; particulate matter; human toxicity, non-cancer; human toxicity cancer; acidification; freshwater eutrophication; marine eutrophication; terrestrial eutrophication, freshwater ecotoxicity; land use; water use; fossil resource use.

Papadaki et al., (2016) used LCA impact assessment method using Simapro 7.1 software and the CML2 baseline 2000 method, for the potential environmental damage of airborne, liquid and solid emissions by means of appropriate equivalence factors to selected reference compounds.

For hexane extraction has been used as follows by Paramita, 2012: from technosphere (oil mill, tap water, hexane, phosphoric acid, electricity and heat) and to atmosphere (hexane). The following procedures have been used for supercritical fluid extraction with CO_2: from the technosphere (CO_2, electricity, compression, electricity, cooling water, tap water, and to the atmosphere (CO_2) (Figure 4 a, b).

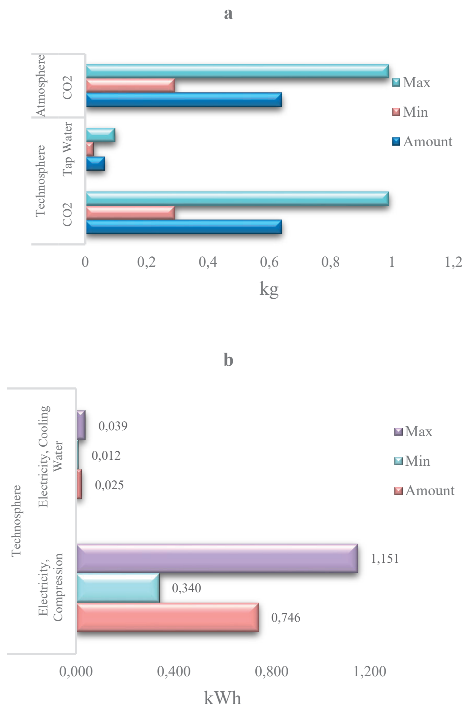

Figure 4. Inventories for supercritical fluid extraction CO_2 ($SCCO_2$) (Paramita, 2012)

Other parameters that were compered in LCA analysis by Paramita et al. (2012): productivities and lipid content of microalgae, nutrient and CO_2 inputs to the growth system, CO_2 compression, daily water need for the whole facility, energy need for water transport and treatment, harvesting via in-pond sedimentation, producing 1 time harvest worth of biomass, harvesting, dewatering, and drying processes, hydrothermal liquefaction, transesterification following hexane or $SCCO_2$ extraction to produce 1 kg of biodiesel, transesterification following hydrothermal liquefaction to produce 1 kg of biodiesel, hydrotreating following hydrothermal liquefaction to process 1 kg of algal oil, comparison non-renewable energy input in using green algae and diatom, hydrotreating. Shi et al. (2018) analysed the GHG emissions and converted to CO_2 eq. using the Intergovernmental Panel on Climate Change (IPCC) 2013 GWP 100a method in the SimaPro software. CO_2, CH_4, and N_2O GWP values were included, with 100-year GWP values of 1, 28, and 265, respectively. Inventories of various inputs has been calculated, including the energy inputs (electricity, heat, and steam), chemicals and solvents, as well as other material inputs. The study conducted seven gate-to-gate LCAs unit technologies and evaluated 14 scenarios of incorporating different harvesting and extraction technology combinations into the full algae life cycle. Harvesting technologies considered included Chitosan flocculation, electrolytic coagulation, membrane harvesting, and acoustic harvesting; while extraction technologies considered included wet separation/fractionation (AlgaFracTM) and acoustic extraction (Figure 5).

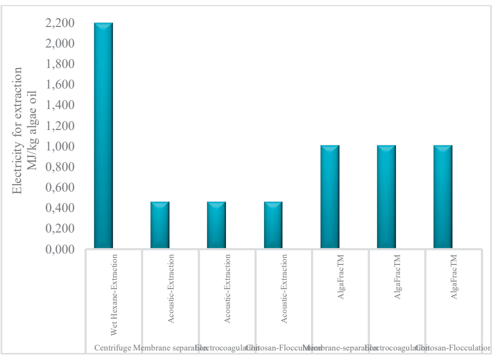

Figure 5. Extraction technologies: Wet Separation/ Fractionation (AlgaFracTM) and Acoustic Extraction, after Shi et al., 2018

RESULTS AND DISCUSSIONS

In the resource efficiency scenario results, Gaber et al. (2022) presented that hydrothermal liquefaction using aqueous phase during cultivation can reduce energy demand, nutrient input, revealed a decreased by 0.8 kg CO_2 from the Baseline Scenario. The authors also compared TFA extracted from microalgae with those from soybean. 1 kg of soybean oil requires far more land than 1 kg of algal TFA, in the context of microalgae cultivation with saltwater instead of tap water. As a result, since soybean production requires inputs like tap water for irrigation, a negative impact from soybean oil production rather than algal TFA was anticipated in the case of water depletion. Medeiros et al. (2022) used N and P from residual sources and energy from photovoltaic systems for microalgae biomass production. The results showed a decrease in energy (61%), carbon footprint (84%), and financial cost (37%).

Nutritional profile of microalgae and fish species per kg DM was also have been presented by Schade et al. (2020), microalgae biomass having higher content of fat and calories then alaska pollack, codfish and tilapia fish (Figures 6 and 7). Related to EPA content, *Nannochloropsis* sp. was highlighted having the highest content of all fish from both capture and aquaculture (Figure 8).

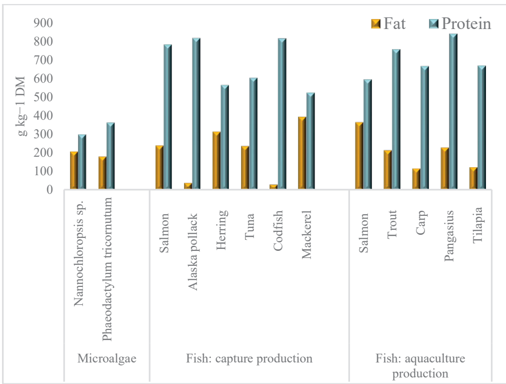

Figure 6. Fat and protein content of microalgae and fish species

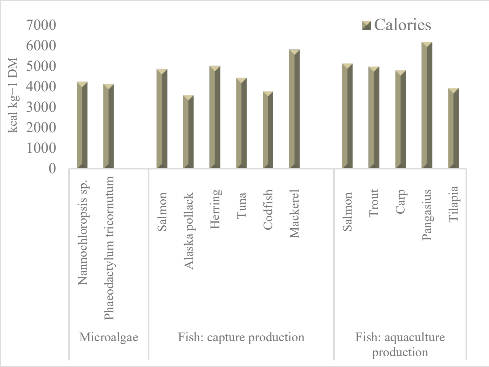

Figure 7. Calories content of microalgae and fish species

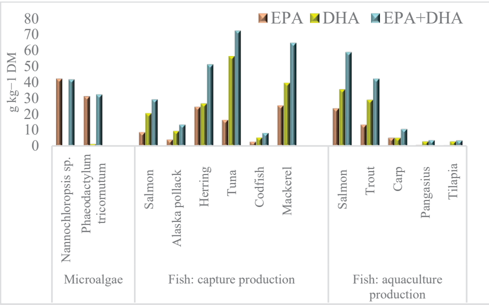

Figure 8. EPA and DHA content of microalgae and fish species

For aquaculture fish production, water and land used were taken into account, global warming was assessed as CO_2 eq. according to IPCC 2013 GWP 100(Directive 2014/24/EU, 2014). Acidification and eutrophication were recorded as SO_2 eq. and PO_4^- eq., respectively, based on CML-IA Baseline EU25 (Directive 2014/25/EU, 2014).
Schade et al. (2020) in their analysis showed that microalgae can be produced with lower environmental impacts than fish production.
Microalgae biomass cultivation that includes the burden of CO_2 production has similar or lower environmental impacts than aquaculture fish. Microalgae cultivation being sustainable in a temperate climate and are able to compete with fish as an alternative nutrient resource. Schade et al. (2020) for CO_2 scenarios the authors found that eutrophication potentials are similar to those of aquaculture fish production and slower emissions than with trout and pangasius.
Since farmed fish requires EPA+DHA as a supplement in its feed, a scenario was developed by supplementing EPA+DHA from microalgae and less from than caught fish. Has been demonstrated that the environmental impact of EPA+DHA production from farms was similar when fish oil from caught fish is replaced with oil from microalgae cultivated in the heterotrophic mode, proving that omega-3 fatty acid-producing in this way could be an alternative to conventional fish oil (Papadaki et al., 2016).
Lopes et al. (2023) developed a mathematical model which allowed the estimation of microalgal production/ processing and the associated environmental impacts and costs. Its conceptual design and validation were undertaken on the basis of real industrial-scale production data obtained using three different microalgae: *Nannochloropsis* sp., *Dunaliella* sp., and *Spirulina* sp. Regarding production costs, Scenario 1 (no water recirculation applied and the use of industrial gaseous CO_2) was revealed to be the most economic option, whereas Scenario 2 (the use of flue gas as a carbon source) the most expensive strain to produce/process having the lower productivity, which was compensated for on the biorefinery side by the extraction of carotene and glycerol.
The environmental impacts of cultivation and harvesting, drying and extraction stages were evaluated by Papadaki et al. (2016) and showed that *H. pluvialis* is a high rich source of astaxanthin which can be recovered sufficiently using not only organic solvent but also edible vegetable and essential oils. Microwave assisted extraction is considered also a rapid and overall eco-friendly technique suffering though from low yielding due to thermal degradation of carotenoids in long processing times. The maceration and the Soxhlet extraction techniques are highly time consuming, expensive and potentially hazardous due to the large number of solvents used, Soxhlet also exhibits low yielding due to thermal degradation and high energy demand (Figure 9 a, b).

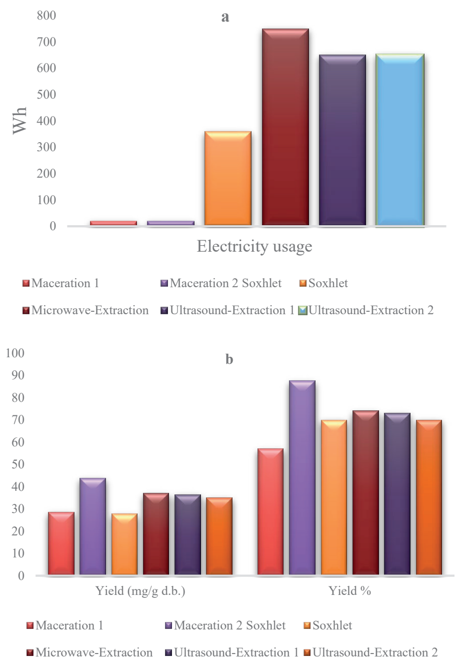

Figure 9. Extraction conditions, energy consumption and yield of *Haematococcus pluvialis* after Papadaki et al., 2016

The overall environmental impacts of the processes showed that abiotic depletion impact is minimized through the recycling of solvents and other materials though the cradle to gate process. The authors revealed that the selected solvents were assumed to be recycled and reused in a rate of 80 %, while vegetable oils were considered to be filtered and reused in a ratio of 50 % regarding scale up and industrial application.

In their study Shi et al. (2018) algae lipid content was assumed to be 25% for all scenarios, lipid density was assumed to be 864 kg per m^3, lower heating value of lipid was 10.5 kWh (37.8 MJ) per kg, and heating value of LEA was assumed to be 4.86 kWh (17.5 MJ) per dry kg.

From economically point of view, the most favorable *Nannochloropsis* sp. was oil, pigment and bioH_2 production via supercritical fluid extraction (SFE) then Soxhlet extraction (SE). From net energy balance and CO_2 emissions analysis, the biodiesel SE + bioH_2 presented better results, but in SFE it's possible to produce high-value oil and pigments with a clean technology free of toxic organic solvents (Ferreira et al., 2013).

Economic feasibility analysis

Shi et al. (2018) revealed that harvesting, drying and milling have an insignificant impact over total costs. The higher share of electricity consumption costs is caused by the relatively long (40 days) period of algae growth and by applied extraction type. It might be advantageous to reduce period of time that will lead to oil and pigment yields decrease, but the decision could be taken through permanent monitoring of the cellular accumulation of this compound. For Soxhlet extraction and pigment supercritical extraction (SFE) used for algal oil production. Although SFE is energetically more intensive, in monetary terms Soxhlet (660.56 €/kg) is almost twice expensive rather than the supercritical one (365.42 €/kg). Inputs like hexane affected the costs of Soxhlet process, making it more expensive. Processing a larger amount of biomass, close to an industrial scale, could lead to a decrease of energy consumption (and associated CO_2 emissions) and costs, as all of them were calculated based on a laboratory scale.

LCA analysis can be used together with TEA, both of them are critical for determining the environmental and economic risks and opportunities of a technology or product before industrial deployment.

For simple models, uncertain parameters of the method include lifetime, discount rate, fuel, consumables costs, and scaling exponents. Moderate systems include equipment sizes, costs, and escalation factors. Both simple and moderate parameters could be considered separated or included in complex models in addition with other parameters like scaling factors, detailed capital costs, operational costs (Barahmand et al., 2022).

CONCLUSIONS

The review brings new insides on LCA as tool for the sustainability PUFA extraction from microalgae.

The review highlights that LCA it is a useful analytical environmental management tool that can provide the environmental impacts from cradle to gate of microalgae production. Also, the analysis provides information related to PUFA extraction, but it has some limitation, and it can be recommended to be used together with techno-economic assessments (TEA).

For PUFA extraction, harvesting, drying and milling were found to be not significant over total costs.

Inputs like conventional solvents affect the cost of the extraction processes and environment. Even that supercritical extraction requires a higher energetic cost, overall, it is cheaper than conventional ones.

The gathering and evaluation of studies analyzing the life cycle sustainability of microalgae lipid extraction systems is critical for the dissemination of microalgae systems, the utilization of their current potential, and the determination of future vision. As a result, it is recommended that future studies examine life cycle economic, social, and environmental sustainability.

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