

LIFE CYCLE OF BIOFERTILIZER PRODUCTION FROM MICROALGAL BIOMASS: TECHNICAL ASPECTS AND FUTURE PERSPECTIVES

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Abstract The increasing use of biofertilizers in agriculture requires an assessment of environmental impacts associated with their production, which can be addressed through Life Cycle Assessment (LCA) to support process optimization and sustainability. Among emerging alternatives, microalgae-based biofertilizers have received growing attention. This study presents a bibliometric review of 21 original research articles published between 2020 and 2025 that applied LCA to microalgal biofertilizer production, with data collected from the Scopus database and analyzed using VOSviewer software. The reviewed studies indicate that microalgal biofertilizers can exhibit improved environmental performance compared to synthetic fertilizers. Specific case studies report reductions of up to 38.65% in environmental impacts and mitigation of up to 52.56%, particularly when strategies such as wastewater reuse and optimization of cultivation stages are adopted. LCA applications mainly focus on impact categories such as global warming potential, eutrophication, acidification, ecotoxicity, and resource consumption, with greenhouse gas emissions and energy demand identified as the main contributors. Cultivation and harvesting stages stand out as the primary environmental hotspots. Despite the strong environmental focus, economic and social analyses remain limited. Future perspectives include integrating microalgae cultivation with wastewater treatment, adopting low-energy harvesting technologies, and applying the biorefinery concept, reinforcing the need for harmonized LCA methodologies and integrated sustainability assessments.

Keywords: LCA; algae; bioinputs; challenges; opportunities; biofertilizer.

CICLO DE VIDA DA PRODUÇÃO DE BIOFERTILIZANTES A PARTIR DE BIOMASSA MICROALGAL: ASPECTOS TÉCNICOS E PERSPECTIVAS FUTURAS

Resumo: O uso crescente de biofertilizantes na agricultura exige a avaliação dos impactos ambientais associados à sua produção, o que pode ser realizado por meio da Avaliação do Ciclo de Vida (ACV) para apoiar a otimização de processos e a sustentabilidade. Entre as alternativas emergentes, os biofertilizantes à base de microalgas têm

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recebido atenção crescente. Este estudo apresenta uma revisão bibliométrica de 21 artigos originais publicados entre 2020 e 2025 que aplicaram a ACV à produção de biofertilizantes microalgais, com dados coletados na base Scopus e analisados no software VOSviewer. Os estudos revisados indicam que os biofertilizantes microalgais podem apresentar melhor desempenho ambiental em comparação aos fertilizantes sintéticos. Estudos de caso específicos relatam reduções de até 38,65% nos impactos ambientais e mitigação de até 52,56%, especialmente quando são adotadas estratégias como o reúso de efluentes e a otimização das etapas de cultivo. As aplicações de ACV concentram-se principalmente em categorias como potencial de aquecimento global, eutrofização, acidificação, ecotoxicidade e consumo de recursos, sendo as emissões de gases de efeito estufa e a demanda energética os principais contribuintes. As etapas de cultivo e colheita destacam-se como os principais pontos críticos ambientais. Apesar do foco ambiental, análises econômicas e sociais permanecem pouco exploradas. As perspectivas futuras incluem a integração do cultivo de microalgas com o tratamento de efluentes, tecnologias de colheita de baixa demanda energética e a aplicação do conceito de biorrefinaria, reforçando a necessidade de metodologias de ACV harmonizadas e avaliações integradas de sustentabilidade.

Palavras-chave: ACV; algas; bioinsumos; desafios; oportunidades; biofertilizante.

1 INTRODUCTION

By 2050, the global population is projected to reach 9.5 billion, with 840 million people still facing hunger by 2030 (Kumar *et al.*, 2022; Miranda *et al.*, 2024), necessitating increased food production without expanding agricultural land, thus raising fertilizer demand (Osorio-Reyes *et al.*, 2023). Synthetic fertilizers, composed of nitrogen, phosphorus, and potassium (Khan *et al.*, 2023; Sharma *et al.*, 2021), cause environmental issues like eutrophication, soil degradation, and heavy metal accumulation in plants (Daramola & Hatzell, 2023; Khan *et al.*, 2023). Their production relies on non-renewable resources like phosphate rocks and natural gas, facing scarcity and geopolitical constraints (Acién Fernández *et al.*, 2018; Sniatala *et al.*, 2023; Ferreira *et al.*, 2023; Miranda *et al.*, 2024), highlighting the need for sustainable alternatives.

Biofertilizers, made from microorganisms or biomass (bacteria, fungi, algae), enhance soil health and plant growth by improving nutrient availability (Chen *et al.*, 2018; Das *et al.*, 2019; Silambarasen *et al.*, 2021; Thomas & Singh, 2019). They improve long-term soil fertility, nutrient efficiency, and microbial activity while reducing agrochemical use (Osorio-Reyes *et al.*, 2023; Zarezadeh *et al.*, 2019).

Microalgal biofertilizers are considered sustainable due to CO₂ uptake during photosynthesis, while their plant growth benefits are mainly attributed to nutrient-rich biomass and putative phytohormone-related signaling effects inferred from plant responses (Al-Jabri *et al.*, 2021; Alvarez *et al.*, 2021; Parmar *et al.*, 2023). Cultivable in diverse environments like wastewater, they aid pollutant removal and nutrient recovery (Coppens *et al.*, 2016; Ferreira *et al.*, 2020; Rupawalla *et al.*, 2021; Sharma *et al.*, 2021).

Recent market analyses indicate that the global biofertilizer market was valued at approximately USD 2.53 billion in 2024 and is projected to reach USD 6.34 billion by 2032, exhibiting a Compound Annual Growth Rate (CAGR) of about 12.31% over the 2025–2032 period, reflecting the growing demand for sustainable agricultural inputs (Fortune Business Insights, 2025). According to Future Market Insights (2025), the microalgae fertilizers sector is projected to grow from approximately USD 15.0 billion

in 2025 to over USD 35.0 billion by 2034, corresponding to a CAGR close to 10%, a difference largely explained by the broader scope of microalgae-based products, which often include biofertilizers, biostimulants, and algae-enriched formulations. This expansion is closely associated with the growth of organic and sustainable farming practices, as global organic agriculture is expected to surpass 75 million hectares by 2028, reinforcing the demand for environmentally friendly bio-inputs such as biofertilizers (Ramakrishnan *et al.*, 2023).

In this expanding market context and increasing alignment with organic agriculture, microalgal biofertilizer production emerges as a promising yet still developing technology, requiring further investigation to comprehensively assess its environmental impacts. In this regard, Life Cycle Assessment (LCA) is a well-established and essential tool for evaluating and optimizing the environmental performance, efficiency, and sustainability of microalgal production systems (Amann *et al.*, 2018; Castro *et al.*, 2020a). Moreover, LCA provides scientifically grounded insights to support environmental policymaking and the development of more sustainable agricultural practices, ultimately contributing to long-term food and environmental security (Ketzer *et al.*, 2018; Magalhães *et al.*, 2021).

In this context, this study presents a bibliometric review of research published between 2020 and 2025 that applies LCA to microalgal biofertilizer production, aiming to identify methodological trends, assess the current state of knowledge, and highlight future perspectives for optimizing the environmental performance of these systems.

2 METHODOLOGY

The bibliometric review aimed to assess the current state of knowledge, identify research trends, and discuss future perspectives on the application of Life Cycle Assessment (LCA) to microalgal biofertilizers. Data collection was conducted using the Scopus database, with searches performed in the Title, Abstract, and Keywords fields employing the terms “LCA” OR “Life Cycle” AND “Biofertilizer” OR “Fertilizer” AND “Microalgae”. The initial search yielded 57 records at the time the search was conducted, of which 21 original research articles published between 2020 and 2025 were selected, as they specifically focused on microalgal biofertilizer production evaluated through LCA. Review articles, conference proceedings, and studies outside the scope of the research objectives were excluded.

All selected articles were read in full due to the limited number of publications. Bibliometric data were exported in CSV format and analyzed using VOSviewer (version 1.6.20) to construct networks based on author keywords (Ketzer *et al.*, 2018; Magalhães *et al.*, 2021). Future perspectives and research opportunities were identified based on the discussion and conclusion sections of the selected studies.

3 RESULTS AND DISCUSSIONS

3.1 Findings from Bibliometric Analysis

This bibliometric analysis maps trends and advances in Life Cycle Assessment (LCA) applied to microalgal biofertilizers from 2020 to 2025, revealing significant growth in

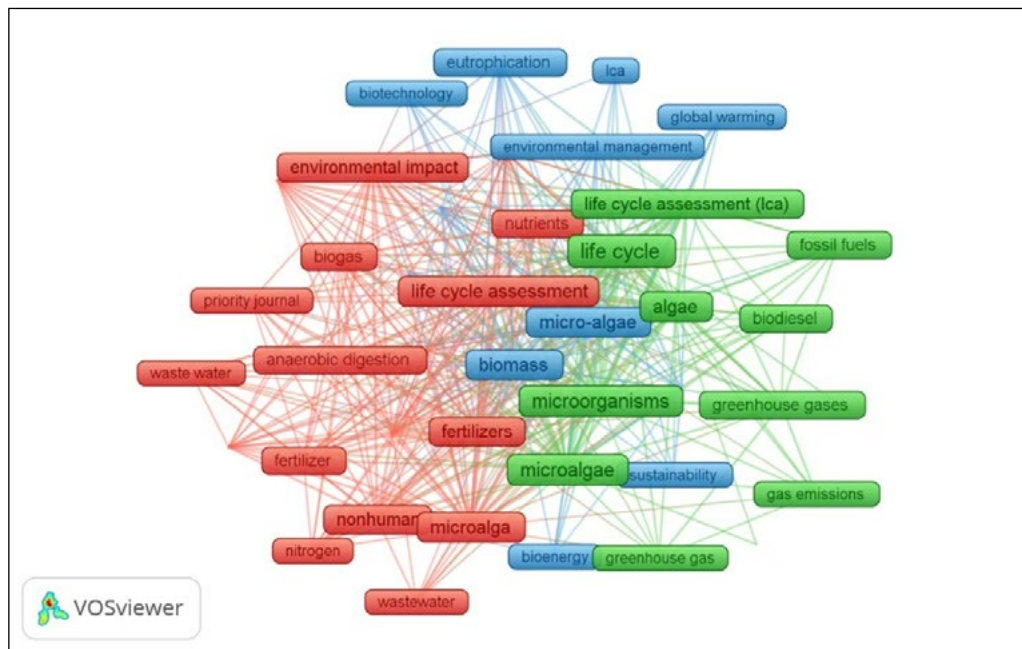
publications driven by increasing academic and industrial interest in sustainable microalgae-based technologies. The global relevance of microalgal biofertilizers lies in their potential to partially replace conventional mineral fertilizers and reduce the environmental impacts associated with agricultural production.

Brazil and China lead the scientific output in this field, with 8 and 5 publications, respectively, reflecting their high consumption of mineral fertilizers – Brazil accounting for 8.3% and China for 24% of the global nutrient market – and their investments in green technologies for sustainable agriculture (Dyuzheva & Tinkova, 2019; Pauli de Bastiani *et al.*, 2024). Spain, Italy, and India each account for 3 publications within the analyzed dataset and, despite the lower number of studies, play a strategic role in the development of microalgal biofertilizers due to their distinct regulatory frameworks, agro-climatic conditions, and agricultural demands.

In the European context, particularly in Spain and Italy, studies predominantly frame microalgae-based products as plant biostimulants, in line with the European Union Fertilizing Products Regulation (EU) 2019/1009. These studies emphasize improvements in nutrient use efficiency, stress tolerance, and environmental performance rather than the direct supply of nutrients (European Union, 2019; Arashiro *et al.*, 2022; Crippa *et al.*, 2022). In contrast, Indian studies frequently highlight the direct biofertilizer potential of microalgae and cyanobacteria, especially blue-green algae, due to their capacity for biological nitrogen fixation and partial substitution of synthetic nitrogen fertilizers in rice-based cropping systems (Devi *et al.*, 2023). This approach is supported by regulatory flexibility under the Fertilizer (Control) Order (FCO), 1985, combined with local agronomic practices, reinforcing the relevance of microalgal biofertilizers for sustainable intensification and nutrient management in developing agricultural economies (Government of India, 1985; Singh *et al.*, 2016).

Figure 1 presents the thematic map derived from the selected studies that conducted Life Cycle Assessments (LCA) on biofertilizers produced from microalgal biomass.

Figure 1 - Thematic map obtained from articles found using the terms “LCA” OR “Life Cycle” AND “Biofertilizer” OR “Fertilizer” AND “Microalgae”



The bibliometric analysis identifies three main clusters in the term co-occurrence network: the red cluster emphasizes environmental impacts, anaerobic digestion, wastewater, and fertilizers, focusing on the environmental effects of microalgal fertilizer production; the green cluster centers on life cycle analysis, microalgae, microorganisms, and greenhouse gas emissions, highlighting the integration of microbiological processes within LCA frameworks; and the blue cluster addresses eutrophication, global warming, biotechnology, and environmental management, reflecting sustainability and governance perspectives. Emerging themes such as bioenergy, greenhouse gas emissions, and sustainability indicate a growing interest in the role of microalgal biofertilizers in emission mitigation and circular bioeconomy strategies.

Within this context, LCA emerges as a fundamental methodological framework for evaluating the environmental performance of microalgal biofertilizer systems. According to ISO 14040 (2006), LCA comprises four phases: (a) goal and scope definition, (b) life cycle inventory, (c) life cycle impact assessment, and (d) interpretation.

3.2 Technical and Methodological Aspects of LCA Studies

In accordance with the methodological framework established by ISO 14040 (2006), this section analyzes the technical and methodological choices adopted in Life Cycle Assessment (LCA) studies applied to microalgal biofertilizers. The reviewed literature shows considerable variability in goal and scope definition, system boundaries, functional

units, process configurations, and impact categories, which directly affects the robustness, comparability, and interpretation of results.

Given the multifunctional nature of microalgal biofertilizers, such as nutrient recovery, wastewater treatment, soil amendment, and crop productivity enhancement harmonized methodological structure is essential to ensure consistent assessments. Therefore, following ISO 14040 (2006) requirements, this section synthesizes and compares the main methodological assumptions reported in existing studies, focusing on goal and scope definition, life cycle inventory modeling, impact assessment methods, and allocation approaches, while identifying methodological gaps and opportunities for improvement. Table 1 presents the data adopted by different authors for the elaboration of LCA studies, with particular emphasis on the goal and scope definition phase, as recommended by ISO 14040.

Table 1 - Data adopted by different authors for the elaboration of an LCA, mainly in the phases of the definition of goals and scope

Microalgae specie	System boundaries	Functional unit	Process adopted	Impact categories*	References
<i>Scenedesmus vacuolatus</i>	Cradle to an intermediate point	Materials, construction, and initial operation that were applied	Photobioreactor filled with water, where microalgae circulate through methacrylate tube (bubble column)	GWP	Villalba <i>et al.</i> 2023
<i>Chlorella vulgaris</i>	Cradle to gate	12.5 m ³ /h of wastewater treatment	Biomass production, mechanical dewatering, thermal conditioning, hydrothermal carbonization, and hydrochar separation	GWP, OF, FMPF, OF-TE, TA, FE, ME, TET, ME, HCT, FRS, and WC	Castro <i>et al.</i> 2023
<i>Chlorella vulgaris</i> , <i>Didymocystis inermis</i> , <i>Tetradesmus obliquus</i> and <i>Navicula sp.</i>	Cradle to field	1 kg of corn plant cultivated for 30 days	Cultivation, harvesting, dry biomass, pellet production, corn planting	CC, WC, FD, ME, FEP, TA, OD, and FPMF	Pereira <i>et al.</i> 2023
<i>Chlorella so.</i> , <i>Scenedesmus sp.</i> , and <i>Chlamydomonas sp.</i>	Cradle to gate	1 kg of microalgal biomass	Growth and acclimatization of the inoculum microalgae, the operation of the ORP (open raceway pond) and FP-PBR (photobioreactor flat panel), and the destination of byproducts	GWP, CC, OD, WE, TET, HTC, HT, WA, TA, EUT, FPMF, and WS	Prado <i>et al.</i> 2023
<i>Scenedesmus obliquus</i> , <i>Monoraphidium minutum</i> and <i>Picochlorum celeri</i>	Cradle to gate	1 kg of biomass production in total solids	Cultivation, harvesting, conversion, use, post use	Energy demand, carbon footprint, and financial cost	Medeiros and Moreira 2022
<i>Spirulina platensis</i>	Cradle to gate	1 m ³ of treated water, and 1 kg of microalgal biomass produced	HRAP (high-rate algal ponds), filtration, centrifuge, transportation	GWP, SOD, TA, ME, FEP, TET, HCT, MRS, FRS, and FPMF	Arashiro <i>et al.</i> 2022
<i>Chlorella vulgaris</i>	Cradle to field	100 kg of plant and 1 ha of planted area	Cultivation, harvesting, drying, soil preparation and plant growth	CC, FE, FPMF, TA, TET, and FRS	Silva <i>et al.</i> 2022
<i>Chlorella sp.</i>	Cradle to gate	N/A	Cultivation, harvesting, spinach plantation	CO ₂ emissions, land footprint, and water footprint	Rupawalla <i>et al.</i> 2021

Microalgae specie	System boundaries	Functional unit	Process adopted	Impact categories*	References
Mix of microalgae	Cradle to gate	163 g of phosphorus	HRAP cultivation, drying, and granulation	CC, FET, TA, FE, FPMF, TET and, FRS	Castro <i>et al.</i> 2020

*GWP: Global Warming; OF: Ozone formation; OF-TE: Terrestrial ecosystem; LO: Land occupation; GWP: Global Warming; ME: Marine eutrophication; TE: Terrestrial eutrophication; TET: Terrestrial ecotoxicity; SOD: Stratospheric Ozone Depletion; HT: Human toxicity; CC: Climate change; FPMF: Fine particulate material formation; TA: Terrestrial acidification; FE: Freshwater eutrophication; FET: Freshwater ecotoxicity; MEP: Marine ecotoxicity; EUT: Eutrophication; HTC: Human carcinogenic toxicity; MRS: Mineral resource scarcity; FRS: Fossil resource scarcity; WC: Water consumption; WA: water acidification; WS: Water scarcity; HT: human toxicity; HH: Human health.

The aim of Life Cycle Assessment (LCA) studies on microalgal biofertilizers focuses on defining key objectives, such as the intended application, study rationale, and target audience, while the scope outlines the functional unit, system boundaries, impact categories, and selected processes (Castro *et al.*, 2023; Villalba *et al.*, 2023). Most studies evaluate the environmental impacts of biofertilizer production (Castro *et al.*, 2023; Villalba *et al.*, 2023) and field application (Pereira *et al.*, 2023; Rupawalla *et al.*, 2021; Silva *et al.*, 2022), with some comparing biofertilizers to synthetic fertilizers (Castro *et al.*, 2020a; Pereira *et al.*, 2023).

The biorefinery concept is integrated in studies like Castro *et al.* (2020a), which assessed biofertilizer and biodiesel production, and Arashiro *et al.* (2022), which evaluated natural pigments, biogas, and biofertilizers from microalgae cultivated during effluent treatment. Medeiros and Moreira (2022) extended their LCA to include technical and economic analyses of biofertilizer production.

The choice of functional units is directly linked to system boundaries. “Cradle-to-gate” studies, centered on production, typically use biomass yield or nutrient recovery as functional units (Castro *et al.*, 2020a; Prado *et al.*, 2023). In contrast, “cradle-to-field” assessments, extending to field application, adopt crop yield metrics, such as 1 kg of corn over 30 days (Pereira *et al.*, 2023) or 100 kg of plant yield per hectare (Silva *et al.*, 2022). For effluent treatment, functional units are based on treated volume, e.g., 12.5 m³/h for *Chlorella vulgaris* in agro-industrial effluent (Castro *et al.*, 2023) or 1 m³ for *Spirulina platensis* in domestic and industrial effluent (Arashiro *et al.*, 2022).

The selection of “cradle-to-gate” or “cradle-to-field” boundaries depends on the study’s focus, nutrient recovery, CO₂ mitigation, or agricultural productivity, with the latter increasingly recommended for its ability to capture soil, microbial, crop, and emission impacts (Castro *et al.*, 2023; Pereira *et al.*, 2023; Silva *et al.*, 2022; Wu *et al.*, 2021).

Villalba *et al.* (2023) introduced a “cradle-to-certain-point” approach, focusing on system design and operation to optimize sustainability by considering material selection and strategies to minimize environmental impacts. This approach highlights the flexibility of LCA in addressing specific stages of the production process, offering insights into early-stage optimization for sustainable outcomes.

In the Life Cycle Inventory (LCI) phase, inputs and outputs of the biofertilizer production system are quantified, with the production process being a critical component.

Microalgal biofertilizer production involves: (a) cultivation under controlled conditions (light, temperature, pH, nutrients, aeration) in open systems (e.g., raceway tanks) or closed photobioreactors (Chew *et al.*, 2018; Castro *et al.*, 2020b; Moges *et al.*, 2020); (b) biomass harvesting via centrifugation, filtration, flotation, or sedimentation; (c) drying (air, spray, or vacuum) and processing into powder, granules, or liquid; and (d) formulation with micronutrients, amino acids, or growth promoters (Dineshkumar *et al.*, 2020; Marks *et al.*, 2019; Nayak *et al.*, 2019; Do Nascimento *et al.*, 2015; Miranda *et al.*, 2024; Pereira *et al.*, 2023).

Cultivation methods vary, with open systems like semicircular tanks used by Pereira *et al.* (2023) for *Chlorella vulgaris* (17 days) and Arashiro *et al.* (2022) for *Spirulina platensis* (8 days), or photobioreactors proposed by Villalba *et al.* (2023) for *Scenedesmus vacuolatus*. Final product forms include powder, granules, or liquid, tailored to application needs.

Harvesting techniques differ across studies, impacting efficiency and sustainability. Gravity sedimentation (Medeiros & Moreira, 2022; Prado *et al.*, 2023), chemical coagulation with NaOH (Pereira *et al.*, 2023; Castro *et al.*, 2020a; Silva *et al.*, 2022), electroflocculation (Rupawalla *et al.*, 2021), and filtration (Medeiros & Moreira, 2022; Marangon *et al.*, 2021) are common.

Post-harvest, biomass may undergo dehydration (Rupawalla *et al.*, 2021), oven drying at 35 °C and pelletization (Silva *et al.*, 2022; Pereira *et al.*, 2023), or hydrothermal carbonization at 130 °C for nutrient-rich hydrochar (Castro *et al.*, 2023). Anaerobic digestion is used in effluent treatment studies, with digestate applied as fertilizer (Arashiro *et al.*, 2022). These variations highlight critical process points affecting energy use, nutrient retention, and economic viability (Ferreira *et al.*, 2020; Gonçalves *et al.*, 2023; Renganathan *et al.*, 2024).

Table 2 outlines diverse LCI databases, software, Life Cycle Impact Assessment (LCIA) methods, and allocation approaches, reflecting the varied methodologies used to evaluate environmental impacts (Castro *et al.*, 2020a; Dyuzheva & Tinkova, 2019; Pauli de Bastiani *et al.*, 2024). The diversity in LCA approaches underscores the need for standardized methodologies to enhance comparability and guide sustainable microalgal biofertilizer production.

Table 2 - Data adopted by different authors for the elaboration of an LCA, from the LCI, LCIA and interpretation

LCI database	Software	LCIA method*	Allocation method	Main impacts results	Reference
Ecoinvent and Product Environmental Footprints (PEF)	2030 Calculator by Doconomy	IPCC 2021 GWP 100 impact model	N/A	The system would need 11.11 years to offset its CO ₂ emissions and would result in a net negative impact of 27 tons of CO ₂ over its material lifespan	Villalba <i>et al.</i> , 2023
Ecoinvent	SimaPro	ReCiPe 2016	N/A	Solid biofuel production had higher environmental impacts: 2 times more on Human Health, 1.6 times on Ecosystems, and 4.3 times on Resources compared to biofertilizer production	Castro <i>et al.</i> , 2023

LCI database	Software	LCIA method*	Allocation method	Main impacts results	Reference
Ecoinvent	SimaPro	ReCiPe 2016	Allocation default related to "rest of the world" (RoW)	MB-based fertilizer improved the environmental performance compared to chemical fertilizer by up to 38.65 % and, the adopted strategy favored the mitigation of environmental impacts by up to 52.56 % compared to chemical fertilizer	Pereira <i>et al.</i> , 2023
APHA and Ecoinvent	SimaPro	ReCiPe 2016 and IMPACT World +	N/A	The ORP cultivation system showed worse environmental performance than FP-PBR, mainly due to electricity use, MB application in soil, PCS discharge into water (ORP), and ammonia emissions (FP-PBR)	Prado <i>et al.</i> , 2023
Ecoinvent	OpenLCA	N/A	Cut-off criteria allocation	In scenario S1, fertilizer supply contributed most to energy demand (52%) and carbon footprint (61%), while in S2 electricity supply dominated (51% and 48%); using residual N and P and solar energy reduced energy demand by up to 61%, carbon footprint by 84%, and cost by 37%	Medeiros and Moreira, 2022
Ecoinvent	SimaPro	ReCiPe 2016	N/A	Digestate reuse in agriculture, in urban wastewater treatment, was the main contributor to Terrestrial Ecotoxicity (66% of impacts) due to heavy metal concentrations	Arashiro <i>et al.</i> , 2022
Ecoinvent	SimaPro	ReCiPe	Allocation at the point of substitution - System (APOS, S)	Replacing chemical coagulation with gravitational sedimentation to harvest biomass reduced carbon footprint by 76.33%, and decreased impacts on freshwater ecotoxicity (-24.13%), terrestrial ecotoxicity (-25.72%), and acidification (-68.62%)	Silva <i>et al.</i> , 2022
N/A	Model developed for Roles <i>et al.</i> (2020)	N/A	N/A	Replacing the most effective Synthetic Fertilizer-dose with Algae Fertilizer lowered the Replacing the most effective synthetic fertilizer dose with algae fertilizer shifted the annual carbon footprint from +3.644 to -6.039 kg CO ₂ /m ² , turning the process into a carbon sink	Rupawalla <i>et al.</i> , 2021
Ecoinvent	SimaPro	ReCiPe 2016	N/A	Phosphorus was recovered from meat processing effluent in a high-rate algal pond, with the overall biofertilizer chain causing 3.17 kg CO ₂ eq of climate change impacts	Castro <i>et al.</i> , 2020

*LCIA Methods abbreviation: IPCC: International Panel on Climate Change.

The Life Cycle Impact Assessment (LCIA) phase of LCA studies on microalgal biofertilizers prioritizes environmental impacts, driven by global warming concerns and emission regulations (Sproul *et al.*, 2019). Key categories include global warming potential (GWP), climate change, carbon footprint, eutrophication, acidification, terrestrial/aquatic ecotoxicity, and resource consumption (water, energy, agricultural inputs) (Castro *et al.*, 2023; Rupawalla *et al.*, 2021; Pereira *et al.*, 2023; Prado *et al.*, 2023; Silva *et al.*, 2022).

GWP, measuring emissions in CO₂ equivalents, is critical but varies across studies due to geographic and methodological differences (Meng & McKechnie, 2019; Sproul *et al.*, 2019). However, the strong emphasis on GWP often masks burden shifting to other impact categories, such as eutrophication and ecotoxicity, which are particularly relevant for agricultural systems. This imbalance reflects a broader limitation in current LCIA applications, where climate-centric metrics dominate decision-making, potentially overlooking localized and long-term soil and water impacts.

Microalgal biofertilizers outperform synthetic fertilizers by reducing emissions, non-renewable resource use, and soil/water contamination, particularly when using wastewater (Alvarez *et al.*, 2021; Braun *et al.*, 2024; El Attar *et al.*, 2022; Renganathan *et al.*, 2024). Rupawalla *et al.* (2021) showed algae-based fertilizers lower carbon footprints through carbon assimilation.

Villalba *et al.* (2023) estimated a net -27 tons CO₂ sequestration over the lifespan of facade-based cultivation systems, offsetting emissions in 11.11 years. Silva *et al.* (2022) reported enhanced soil microbial activity, recommending chemical-free harvesting to improve sustainability. Pereira *et al.* (2023) found 38.65% better environmental performance and 52.56% reduced impacts compared to synthetic fertilizers, though NaOH coagulation increased climate change and eutrophication impacts.

NaOH use in harvesting, as in Pereira *et al.* (2023), affects soil pH and NH₄⁺/NH₃ balance, requiring scrutiny. Mandal *et al.* (2018) demonstrated near-neutral pH biochar reduced NH₃ emissions and improved nitrogen retention, offering a sustainable alternative. Nevertheless, the environmental performance of alternative harvesting aids such as biochar remains underexplored in LCIA studies, particularly regarding their own production impacts, availability at scale, and long-term behavior in soils.

Harvesting optimization, such as hybrid biofilm reactor/open tank systems with scraping (Rodrigues de Assis *et al.*, 2020), or gravitational sedimentation (Ferreira *et al.*, 2020), lowers impacts. Silva *et al.* (2022) achieved 76.33% carbon footprint reduction by replacing chemical coagulation with sedimentation, also reducing ecotoxicity and acidification.

Cultivation system choice impacts performance. Prado *et al.* (2023) found semicircular tanks had higher impacts than photobioreactors due to electricity and sewage discharge. Arashiro *et al.* (2018) noted semicircular tanks had lower impacts than activated sludge systems in climate change and resource consumption due to reduced energy needs.

Energy consumption hinders organic fertilizer development. Collotta *et al.* (2019) reported 0.306 kg CO₂ eq./kg biomass using wastewater and flue gas for *Chlorella vulgaris*. Gouveia *et al.* (2016) achieved an 86% energy reduction with solar drying, though scalability needs refinement. Phosphorus recovery and effluent-based cultivation reduce climate change impacts (Castro *et al.*, 2020a), but Arashiro *et al.* (2022) observed increased acidification and ecotoxicity from NH₄⁺ volatilization and heavy metals in effluents. This highlights a critical tension between circular economic strategies and environmental risk management, suggesting that nutrient recovery alone is insufficient to guarantee overall sustainability without adequate control of secondary emissions and contaminants.

Effluent-grown biofertilizers risk heavy metal and microplastic contamination, necessitating quality checks to prevent crop bioaccumulation (Cao *et al.*, 2023; Cajamarca *et al.*, 2019). Microalgae mitigate metal toxicity via complexation (Mehta & Gaur, 2005; Zeraatkar *et al.*, 2016), but chemical analyses are critical. Castro *et al.* (2023) found biofertilizers had lower impacts on health, ecosystems, and resources than biofuels, supporting biorefinery integration. However, the absence of harmonized regulatory thresholds for contaminants in microalgal biofertilizers remains a major bottleneck for

market uptake and fair environmental comparison, indicating that future LCAs should be aligned with emerging regulatory frameworks and include risk-based impact interpretation alongside midpoint indicators.

Life Cycle Impact Assessment (LCIA) in microalgal biofertilizer studies is largely based on the ReCiPe 2016 method implemented in SimaPro, due to its broad acceptance, compatibility with Ecoinvent, and ability to consistently capture climate change, eutrophication, toxicity, and resource-related impacts (Arashiro *et al.*, 2022; Castro *et al.*, 2023; Pereira *et al.*, 2023; Prado *et al.*, 2023; Silva *et al.*, 2022). While this methodological convergence improves internal consistency across studies, it also reinforces reliance on a single impact framework, potentially limiting sensitivity to region-specific conditions and agricultural contexts. Rupawalla *et al.* (2021) partially addressed this limitation by adopting a triple-bottom-line approach, integrating LCA with techno-economic analysis, although social aspects remain weakly explored.

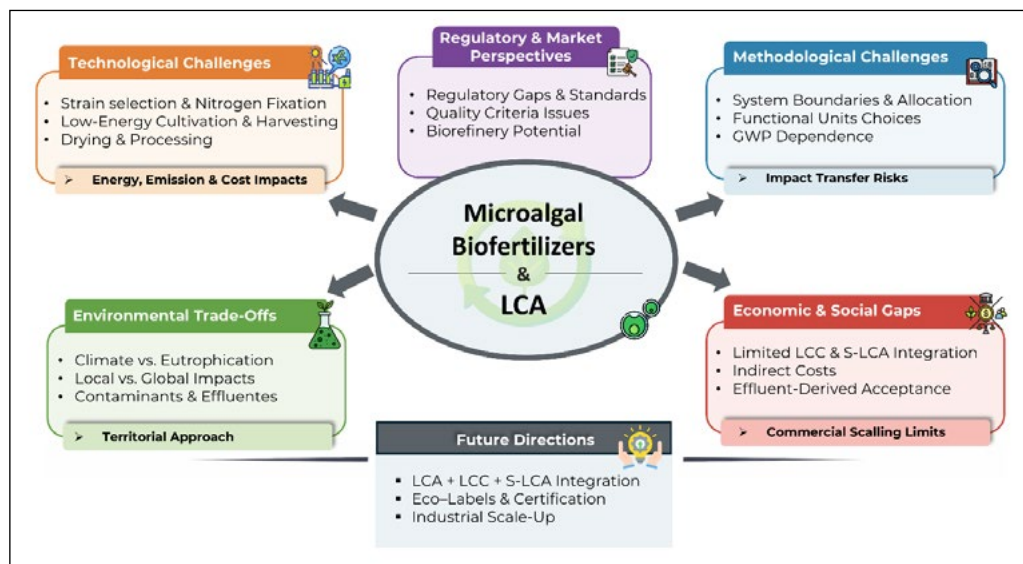
Allocation remains one of the most critical and least harmonized methodological choices in these assessments. The use of mass, energy, volume, or economic-based allocation reflects differing system priorities but leads to substantial variability and ambiguity in results, particularly in multifunctional microalgal systems (Cherubini *et al.*, 2011; Dominguez Aldama *et al.*, 2023; Havukainen *et al.*, 2018). Although ISO 14040 (2006) recommends avoiding allocation through process subdivision or system expansion, several studies either rely on allocation without sufficient justification or fail to clearly report the adopted approach (Arashiro *et al.*, 2022; Castro *et al.*, 2020a, 2023; Medeiros & Moreira, 2022). When explicitly addressed, Pereira *et al.* (2023) apply a “rest of the world” (RoW) approach, while Silva *et al.* (2022) adopt allocation at the point of substitution (APOS), further complicating cross-study comparisons.

Given the strong influence of allocation choices on environmental outcomes, the limited application of sensitivity analyses represents a major methodological weakness. Systematic testing of alternative allocation scenarios is essential to assess result robustness and transparency, particularly in integrated biorefinery and nutrient recovery systems where multifunctionality is inherent (Cherubini *et al.*, 2009; Amann *et al.*, 2018; Dyuzheva & Tinkova, 2019; Pauli de Bastiani *et al.*, 2024).

3.3 Challenges and Future Perspectives

Microalgal biofertilizers have gained increasing attention as a sustainable alternative to conventional fertilizers, but several challenges still affect their development and application. Figure 2 summarizes the main challenges and future perspectives for microalgal biofertilizers assessed through LCA, providing an overview to support the discussion in this section.

Figure 2 – Conceptual framework of challenges and future perspectives for microalgal biofertilizers assessed through life cycle assessment



Microalgal biofertilizer production is advancing, with trends targeting improved efficiency and sustainability. Research focuses on identifying microalgae strains with superior nitrogen fixation and nutrient absorption, alongside developing cost-effective cultivation and harvesting technologies (Yap *et al.*, 2021).

Biotechnological advances, such as genetic engineering, could boost productivity and resilience to environmental stressors (Muthukrishnan, 2022). Optimizing cultivation, harvesting, and processing is critical to increase productivity and reduce resource use, with innovations like efficient photobioreactors and low-energy nutrient extraction methods being pivotal (Castro *et al.*, 2020a; Hussain *et al.*, 2021; Dębowski *et al.*, 2020).

Future LCA perspectives include refining impact assessment methodologies, particularly for water and nutrient footprints (Castro *et al.*, 2023; Osorio-Reyes *et al.*, 2023). Integrating LCA data into decision-making tools, such as environmental certifications and eco-labels, is promising (Balkau *et al.*, 2021; Notarnicola *et al.*, 2015).

However, gaps exist in understanding economic sectors' interest in recovered resources, considering costs and impacts (Samarasinghe & Wijayatunga, 2022). Sustainability analysis, assessing environmental, social, and economic implications, is underexplored but essential to demonstrate biofertilizers' market potential (Rupawalla *et al.*, 2021; Osorio-Reyes *et al.*, 2023; Puglia *et al.*, 2021).

LCA studies must account for local (e.g., terrestrial acidification) versus global (e.g., climate change) impacts, influencing scenario choices (Hauschild, 2005). LCA's limitations in providing definitive conclusions highlight the need for further development (Schaubroeck & Rugani, 2017). The territorial LCA approach, linking impacts to geographic areas, is

gaining relevance, incorporating land use and regional needs but complicating system boundary definitions and data collection (Loiseau *et al.*, 2018; Morais *et al.*, 2018; Prezioso, 2020). This is particularly applicable to biofertilizers due to regional variations in soil, crops, and climate.

Social and economic integration in LCA is critical (Schaubroeck & Rugani, 2017). Josa and Garfi (2023) analyzed microalgae systems for wastewater treatment and bioproduct recovery, noting their circular bioeconomy potential but identifying challenges: low consumer acceptance of wastewater-derived products, regulatory gaps, and limited large-scale demonstration sites.

Castro *et al.* (2023) found biofertilizer production's ecological footprint comparable to solid biofuels, but with lower economic costs (USD 626,152.03 acquisition, USD 36,094.05 operation) versus biofuels (USD 645,452.03, USD 39,710.09). Akbari *et al.* (2020) stress including labor, maintenance, and indirect costs in future economic assessments.

Regulatory gaps hinder biofertilizer adoption. In Brazil, Normative Instruction No. 61 (2020) sets standards for organic fertilizers and biofertilizers, but lacks policies to promote production (Rebelo *et al.*, 2020; Silva *et al.*, 2022). The biorefinery approach, integrating CO₂ biofixation, wastewater treatment, and marketable bioproducts, enhances sustainability and economic viability, reducing costs and providing income for rural producers (Nizami *et al.*, 2017; Russel *et al.*, 2022; Talebi *et al.*, 2021). Future LCA studies should address these gaps to support sustainable microalgal biofertilizer development (Amann *et al.*, 2018; Dyuzheva & Tinkova, 2019; Pauli de Bastiani *et al.*, 2024).

4 CONCLUSIONS

The use of microalgae-based fertilizers presents clear environmental advantages compared to chemical fertilizers, particularly by reducing dependence on non-renewable resources such as mineral phosphates and nitrogen, and by lowering greenhouse gas emissions from synthetic fertilizer production. Their cultivation can also integrate nutrient recovery from wastewater and agricultural residues, reinforcing the circular economy potential of this model.

However, cultivation and harvesting remain the most environmentally burdensome stages, mainly due to high energy demand and chemical inputs. Advancing sustainable techniques and optimizing cultivation systems are therefore essential to ensure the viability and competitiveness of microalgal biofertilizers. Despite several life cycle studies, there are still significant research gaps regarding social and economic impacts, which are crucial to demonstrate the overall sustainability of these products.

Prospects include the simultaneous treatment of effluents with microalgae cultivation, which has been shown to reduce environmental impacts, and the application of the biorefinery concept to obtain multiple bioproducts, including biofertilizers. Nonetheless, further research is needed on aspects such as heavy metal residues, while supportive public policies, legislation, and standards remain critical to enable large-scale adoption.

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