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Is the production of microalgae and the derived bioproducts sustainable? A meta-review outlining the challenges and opportunities of circular bioeconomy and zero-waste approaches

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ABSTRACT

Microalgae are a renewable and versatile feedstock for a multitude of bioproducts (protein feeds and foods, high-added value compounds for nutraceuticals and pharmaceuticals, biofuels, biofertilizers, and bioplastics), offering the potential for CO_2 bio-sequestration. While microalgae-based production systems have garnered significant scientific interest, their techno-economic-environmental viability is still challenged by many limitations. Key research questions emerge: What are the prospects for scaling up microalgae-based production systems? Can microalgal bioproducts achieve true sustainability? This study aims to respond with a systematic meta-review of recent literature containing economic and environmental scientific information. A narrative synthesis is combined with data collection, homogenisation, and appraisal to provide a synoptic framework that captures the latest trends from techno-economic analysis and life cycle assessment, identifying enablers and barriers within a future perspective. The analysis of production costs and GHG emissions reveals a general tendency of poor performance and competitiveness of microalgal bioproducts. However, several optimistic estimates are found within a broad variability of results. Promising strategies are the valorisation of waste streams and the implementation of multi-product biorefinery models, in line with circular bioeconomy and zero-waste principles. The adoption of low-carbon energy technologies and the direct exploitation of sunlight present a additional opportunities to abate GHG emissions. Further potential lies in incentivising pilot projects, which are essential in accelerating process maturity. From a holistic perspective, advancing sustainability will require addressing the social dimension and multi-criteria optimisation. On the other hand, legislative barriers and customer acceptability must be managed through the interaction of academia, industry, and policymakers. Such efforts are crucial to unlock microalgae's full potential and support the microalgal industry's real-world applicability, striving to achieve enhanced market penetration through green and cost-effective production processes.

1. Introduction

Microalgae have emerged as highly promising biological resources due to their ability to fix CO_2 [1–3], their versatility as renewable feedstocks for a wide range of bioproducts – particularly within biorefinery systems [4,5] – and their potential integration with wastewater treatment processes [6,7]. These attributes underscore the broad potential of microalgal biotechnologies across multiple industrial sectors. Technological innovations aimed at optimizing cultivation efficiency and product yields have further expanded this potential [8,9], attracting substantial interdisciplinary interest from the fields of biology, chemical engineering, economics, and environmental science. Fig. 1 shows the rapid growth of scientific output on microalgae: approximately 46,500 articles have been published, including a significant number of review papers (9 %), with the annual publication rate increasing exponentially.

This surge reflects, among others, a vibrant research landscape increasingly focused on scalable and sustainable solutions. Sustainability – commonly conceptualized through the "Triple Bottom Line" of

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environmental, economic, and social dimensions – requires integrative assessment tools to evaluate trade-offs and guide responsible development. Many process-based and life cycle approaches have been applied to bio-based technologies [10]. In this context, techno-economic analysis (TEA) and life cycle assessment (LCA) have emerged as the dominant frameworks for assessing the economic and environmental sustainability of microalgae-based production systems. These methodologies allow for a structured comparison of economic feasibility, environmental impacts, and resource efficiency across different production layouts. However, within the increasing number of TEA and LCA applications and the proliferation of review studies, the available literature presents highly dispersed and often contradictory results, spanning wide ranges (even by several orders of magnitude). While some studies present optimistic estimates, most research offers more cautious or even pessimistic evaluations, both for economic aspects [11,12] and environmental ones [12–14]. As a result, the field still lacks a consensus regarding the true sustainability and industrial viability of microalgal bioproducts.

The existing body of literature of review articles on microalgal biotechnologies, though extensive, is fragmented. Most reviews focus on narrow aspects of the field, such as CO_2 sequestration, biorefinery approach, extraction techniques, wastewater treatment, or specific product classes (e.g., biofuels) or products (e.g., biohydrogen). As a result, they provide partial insights into sustainability outcomes from analyses of TEA and LCA case studies, often lacking cross-comparability and generalizability. A higher-level synthesis that integrates findings across scattered sources is still missing. Such an effort is essential to identify the main trends, overarching patterns, current challenges, gaps in knowledge, and future steps.

This meta-review addresses that gap by systematically analysing review articles that include economic and/or environmental assessments of microalgal systems. It aims to answer two critical questions: *What are the prospects for scaling up and commercialising microalgae-based production systems?* And *can microalgal industries achieve true sustainability?* The analysis centres on recent review studies by summarizing and discussing outcomes and trends from TEA and LCA. The inclusion of both economic and environmental perspectives was motivated by the intention to provide a well-rounded view of sustainability trends. The social dimension, in contrast, was excluded not by omission but due to the lack of systematic studies on this topic within the microalgae field. A synoptic framework is developed for the economic and environmental dimensions, offering a higher-level overview of the state-of-the-art based on evidence from multiple studies, and mapping the most promising development strategies. The most critical methodological challenges are identified with a view toward future research directions, while key enablers and persistent barriers to advancing the sustainability of microalgal bioproducts at scale are examined.

The remainder of this article is structured as follows:

- Section 2, designed for non-specialists, offers a primer on microalgal biotechnologies and introduces the key sustainability assessment tools (LCA and TEA).
- Section 3 details our methodology for identifying, selecting, and examining review studies, classifying case studies, and conducting a structured data analysis. It also outlines the study's limitations.
- Section 4 presents the meta-review results through three lenses: a narrative synthesis of recent review studies, a quantitative data analysis, and an overview of main challenges and prospects for future sustainability evaluations. The perspective is broadened through a Strengths, Weaknesses, Opportunities, and Threats (SWOT) assessment, which provides insights on sustainability and real-world applicability of the microalgal industry.
- Section 5 concludes with a concise summary of the paper's principal take-home messages.

2. Background

2.1. Overview of microalgal biotechnologies

2.1.1. Microalgae

Microalgae are a large class of unicellular or multicellular phytoplanktonic microorganisms that include hundreds of thousands of species and can be classified into several groups [15]. They live individually or in colonies in both freshwater and marine habitats. The biodiversity of microalgae is vast and encompasses species with different morphologies, metabolic capabilities, and ecological roles. In a strict sense, microalgae are eukaryotic organisms. However, the term "microalgae" is also used to include the group of cyanobacteria (also known as "blue-green algae"), which are prokaryotic organisms, but have a similar physiology and ecology and share many biotechnological applications [16]. Microalgae, through photosynthesis, are key primary producers that convert carbon dioxide and sunlight into organic matter (autotrophic metabolism) by using macronutrients (e.g., N and P) [17] and micro-nutrients (e.g., Fe, Mn, Zn, and Cu) [18]. Microalgae play a critical role in global cycles by fixing CO_2 at a higher efficiency rate (10–20 %) than that of terrestrial plants (1–2 %) [19], and they produce a significant portion of the world's oxygen. Some microalgal species can grow through heterotrophic metabolism in the absence of light, replacing CO_2 fixation with organic carbon sources [20]. Another option is the mixotrophic growth regime, in which CO_2 is assimilated via

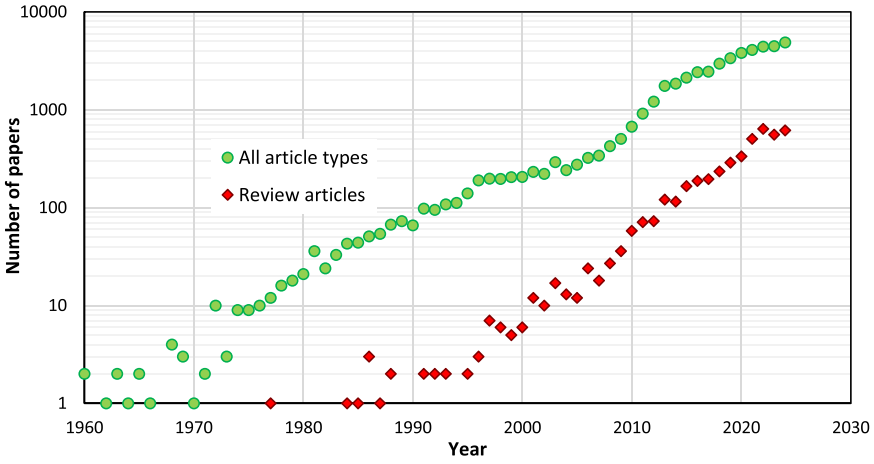

Fig. 1. Papers published on microalgae in the year range 1960–2024. The annual publications were retrieved from a query in the *Scopus* database (www.scopus.com accessed on May 14th, 2025) with the search term "microalgae" within the title, abstract, or keywords (TITL-ABS-KEY).

photosynthesis and exogenous organic carbon is assimilated by the respiratory metabolism, simultaneously or alternatively [20,21]. In the fight against climate change associated with greenhouse gas (GHG) emissions, the photosynthetic path makes microalgae particularly appealing to develop biotechnologies for CO_2 capture from the atmosphere or flue gases [15,22].

2.1.2. Cultivation systems

Different technologies have been developed for microalgae cultivation under (semi-)controlled conditions in artificial systems. They can be divided into two large classes, namely open systems and closed systems. Open bioreactors can, in turn, be divided into raceway ponds, stirred circular ponds, and unstirred ponds [23]. The open raceway pond (ORP) concept is the bioreactor configuration that has been studied the most. Such ponds are generally shallow (about 30 cm in depth to ensure light penetration) and provided with paddle mixers that produce closed-loop circulation. Light and temperature variations are the most significant limiting factors for biomass productivity under outdoor cultivation conditions [23]. Closed photobioreactor (PBR) systems are sealed structures in which the internal environment is isolated from the external one, thereby allowing precise control of the cultivation conditions, such as the light, temperature, and the concentrations of nutrients and carbon dioxide [23,24]. Tubular configurations (horizontal or vertically stacked) are the most frequently used PBR types. Other common configurations are bubble-column, airlift, and flat-panel PBRs. Among the advantages of closed systems, mention can be made of fewer contamination risks, a higher productivity, improved biomass quality and less land use than traditional cultivation methods based on open systems. On the other hand, the common disadvantages are higher installation and operation costs, the need for meticulous maintenance and management, and the risk of biofilm formation [23,24]. Non-conventional systems include membrane PBRs and plastic bag PBRs [23,24]. In addition, attached-growth systems have been developed, where microalgal biomass forms a biofilm on a support and can be collected simply by scraping. These configurations offer several benefits, including reduced dewatering costs and enhanced harvesting efficiency [25] without the need for additional electrical energy or chemical methods [26], and lower space and water consumption [27]. More details on the various microalgal bioreactor types and their advantages and disadvantages can be found in the pertinent literature [23–25]. Heterotrophic growth can be carried out in conventional fermenters, such as those used in the industrial production of pharmaceuticals, food and/or beverages [16,20].

Key factors influencing microalgae biomass productivity can be grouped into environmental, biological, and operational parameters [28–31]:

- Light: intensity, spectral quality, and photoperiod governing photosynthetic efficiency;
- Temperature: strain-specific optima (often 20–30 °C);
- CO_2 and pH: CO_2 supply rate and pH buffering control carbon fixation and nutrient availability;
- Nutrients stoichiometry: macronutrient ratios N:P or C:N:P (heterotrophic mode), micronutrients (Fe, Mn, Zn, etc.);
- Carbon source (heterotrophic mode): type (glucose, acetate, glycerol), concentration and feed strategy;
- Salinity and water chemistry: ionic strength and composition for osmotic balance and nutrient availability;
- Hydrodynamics: mixing intensity and shear affecting light exposure and gas exchange;
- Inoculum density: initial cell concentration influencing self-shading and lag phase;
- Reactor design and scale: open ponds, closed PBRs, non-conventional systems (e.g., attached biofilm), fermenters (stirred-tank or airlift bioreactors, heterotrophic mode), affecting light path, contamination risk, environmental control, mass transfer, and capital cost;
- Biotic stressors: contamination by bacteria, fungi, grazers, or viruses;
- Byproduct inhibition (heterotrophic mode): accumulation of organic acids or ethanol—requires monitoring or in situ removal.

Microalgal cultivation systems require a growth medium (nutrients and water), electrical energy to drive the electromechanical devices (pumps, compressors…) and other equipment (thermoregulation system, LED lighting…), and the infrastructure (bioreactors, equipment, piping and buildings), all of which affect the costs and the environmental impacts of the productive system to various extents. Notably, microalgae can grow directly on municipal or industrial wastewater, simultaneously recovering nutrients and purifying the water. This dual function has driven substantial interest in deploying microalgal systems for wastewater treatment and resource-recovery applications [6,7]. You et al. [6], for example, proposed a pre-selection of microalgal species to identify the most adaptable ones in wastewater to maximise the recovery of N, P, and C resources and biomass productivity. The *Chlorella* genus was found to be suitable for these purposes, but several factors affect the performance of systems that use wastewater, such as the effects of other living microorganisms, the balance of the nutrients (C/N and N/P ratios), the intensity of light and photoperiods, temperature, pH and the cultivation mode. Microalgae can remove various pollutants through different remediation mechanisms, and co-culturing with other organisms (mixed consortia) can provide additional benefits [32]. Indeed, several opportunities arise from harnessing the unique metabolic capabilities of microalgae, including their use in bioremediation across different environmental matrices. However, their optimisation still has to be addressed to enable large-scale applications [33].

2.1.3. The derived bioproducts

The key components of microalgal cell dry matter are protein, carbohydrate, and lipid macromolecules, with percentages that depend on the microalgal species and the cultivation conditions [34,35]. Apart from these major components, microalgae contain small amounts of high-added value constituents, such as pigments (chlorophyll, phycocyanin, astaxanthin and carotenoids), poly-unsaturated fatty acids (PUFAs), peptides and vitamins, which are produced as either primary or secondary metabolites [36]. Cultivation under stress conditions (e.g., nutrient starvation, high salinity, high temperature) can accumulate lipids or carbohydrates along with several high-value secondary metabolites [37]. Because of their complex biochemical composition, microalgae represent a highly versatile renewable raw material that can be used to source a wide array of bioproducts (Fig. 2). Such bioproducts serve multiple industrial sectors and span hydrocarbons (feedstocks for the chemical industry), third-generation and fourth-generation (leveraging genetic and metabolic engineering to enhance production yield and CO_2 intake) biofuels (e.g., biodiesel, bioethanol, biogas, biohydrogen) and bioelectricity [38–43]; feeds, food, nutraceuticals, pharmaceuticals, healthcare products and cosmetics [44–49]; biofertilisers and biostimulants [35,50,51]; biopolymers and bioplastics [52–54].

2.1.4. Microalgal bioprocessing

Microalgal bioprocess systems include multiple steps to obtain the final product(s) [56], as illustrated in Fig. 2. In a generalised process chain, cultivation is followed by harvesting, which is performed to concentrate the biomass via dewatering. Microalgae harvesting involves mechanical, chemical, biological, and electrical methods. Conventional techniques include mechanical methods (centrifugation, sedimentation, and membrane filtration) and flocculation, whereas a range of advanced techniques includes coagulation, bio-, electro-, and magnetic-flocculation, ultrasound/hydrodynamic cavitation, flotation, and phototaxis [57–59]. Cultivation and harvesting in microalgal bioprocess systems are generally referred to as the upstream section, and they are followed by the downstream section, which is devoted to producing the final bioproduct(s) and may include drying, cell disruption,

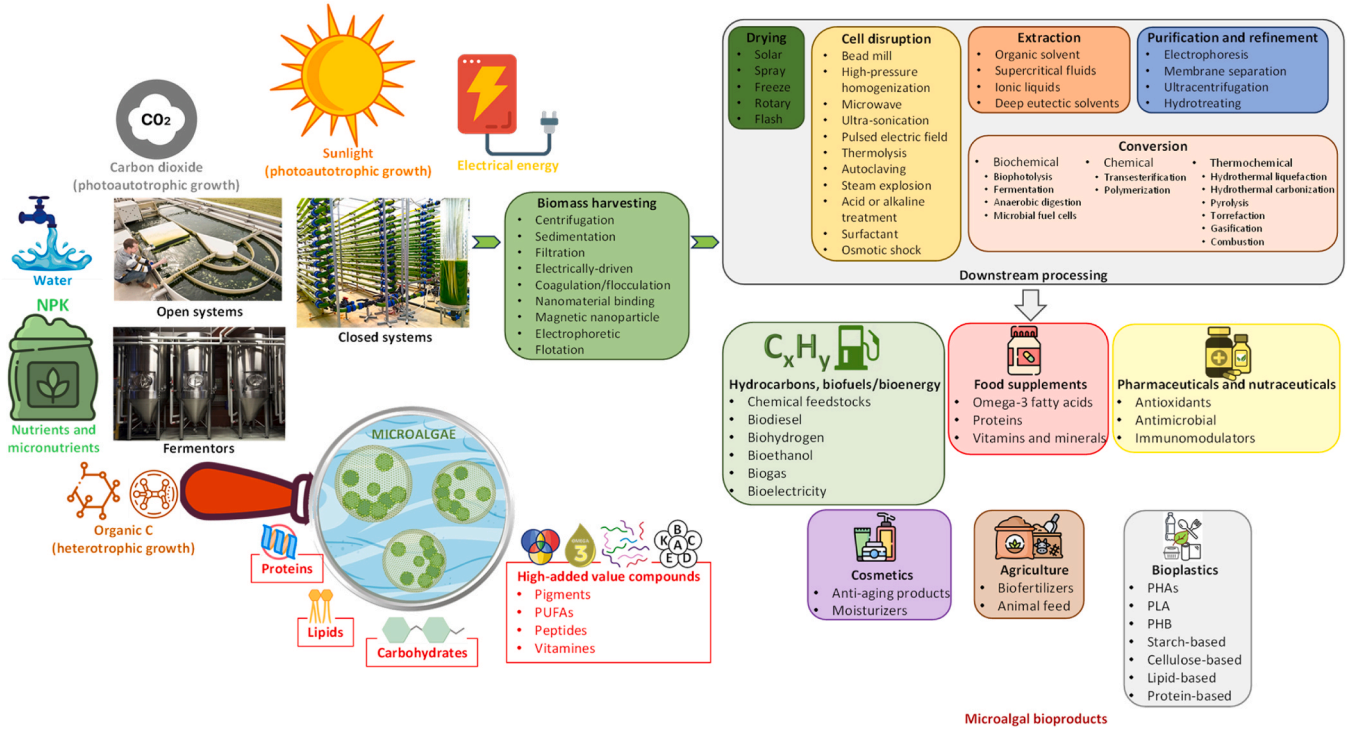

Fig. 2. Overview of microalgae bioprocessing: material and energy inputs, bioreactor configurations, microalgal constituent compounds, harvesting techniques, possible downstream processing steps and techniques, and relevant examples of the obtainable bioproducts. Note that microalgal bioprocessing can follow multiple routes, each incorporating only some of the downstream steps and omitting the others. The images of (i) open systems, (ii) closed systems, and (iii) fermenters are reproduced from (i) Pérez-López et al. [55] with permission from Elsevier, (ii) Gurreri et al. [13], and (iii) Thoré et al. [16] with permission from Elsevier.

extraction, purification, and conversion.

Drying can be performed through several methods (e.g., solar, spray, freeze, rotary, or flash drying) to stabilise the biomass and prevent spoilage for end-use, extraction, or further processing [60–62]. Disruption of the microalgal cells may be performed separately before extraction. The variety of techniques for the disruption of microalgal cellular walls and membranes can be classified as (i) physical or mechanical (bead milling, high-pressure homogenisation, microwave, ultra-sonication, pulsed electric field, thermolysis, autoclaving and steam explosion), (ii) chemical (e.g., acid or alkaline treatments, surfactant disruption, osmotic shock), and (iii) enzymatic methods [63,64].

The extraction step (either combined with cell disruption or applied directly) involves the separation of valuable compounds from the microalgal biomass. Solvent extraction is the most utilised method, but it has the disadvantages of creating environmental concerns (due to the toxicity of conventional organic solvents) and requiring solvent recovery and purification. However, there are several environmentally friendly alternatives, such as supercritical fluids, ionic liquids and deep eutectic solvents [65,66]. The target biomolecules usually have to be separated from the solvent or other components, and thus require a purification step, which can be performed via different methods (e.g., electrophoresis, membrane separation processes, ultracentrifugation) [65]. Bioactive compounds, such as pigments, antioxidants, and vitamins, are extracted from microalgal biomass and then purified and refined for use in pharmaceuticals, nutraceuticals, and cosmetics. Once extracted, soluble proteins are separated from cell debris, clarified and further concentrated to produce protein concentrates or isolates, protein hydrolysates, hydrolysates from protein concentrates, protein hydrolysates from de-oiled cell biomass and small peptides with bioactivity potential [67]. Microalgal biofertilisers are made up of extracted bioactive compounds, including carbohydrates, minerals, trace elements, growth hormones (cytokinins, auxins and auxin-like compounds), betaines and sterols [35].

A conversion step may be required for the microalgal biomass or extracted compounds, depending on the target bioproducts, and various methods are available to carry it out. The primary conversion methods for producing hydrocarbons and biofuels can be grouped into three categories, namely biochemical, chemical and thermochemical technologies [68]. The first group involves the photobiological production of H_2, the alcoholic fermentation of carbohydrates (polysaccharides) to produce bioethanol and other biofuels, the anaerobic digestion of (raw or residual) biomass to produce biogas, and microalgae-based microbial fuel cells to harvest bioelectricity. Chemical conversion via transesterification is the reaction of microalgal lipids (triacylglycerols, commonly referred to as triglycerides) to an alcohol (usually methanol) in the presence of a catalyst (e.g., sodium hydroxide or potassium hydroxide) to produce biodiesel (fatty acid methyl esters), whereby glycerol is obtained as a by-product. Thermochemical processes include (i) the hydrothermal liquefaction (HTL) of wet biomass into biocrude (petroleum-like liquid biofuel), (ii) the hydrothermal carbonisation of dry biomass to produce hydrochar (high-energy density solid fuel), (iii) the pyrolysis of biomass to produce bio-oil, syngas, and biochar, (iv) the torrefaction of dry biomass to produce solid biofuels (biochar), (v) the gasification of biomass to produce syngas, and (vi) the combustion of biomass to recover heat. Microalgal lipids and biocrude (e.g., from HTL or pyrolysis) can be refined and upgraded, typically via catalytic processes of hydrotreating (desulfurization, denitrogenation, deoxygenation, hydrogenation, and saturation reactions) and hydrocracking (cleavage of larger molecules into smaller ones) into various hydrocarbons, which can represent feedstocks for the chemical industry [43] and true drop-in biofuels [69] fully compatible with existing petroleum infrastructure [70] (diesel, gasoline, and biojet fuel). Although hydrotreating of esters and fatty acids represents the most mature route to biojet fuel, its reliance on hydrogen is a major drawback; in contrast, catalytic pyrolysis and HTL can be operated with little to no added hydrogen, making them attractive emerging technologies [70]. Microalgal bioplastics include polyhydroxyalkanoates (PHAs), polylactic acid (PLA), polyurethane (PU), bio-polybutylene succinate (bio-PBS),

polyhydroxybutyrate (PHB), bio-polyethylene (bio-PE), and starch-based, cellulose-based, lipid-based, and protein-based biopolymers. They can be produced through the direct conversion of algal biomass (which is blended with other plastics and sent to some thermochemical or mechanical polymerization process) or the indirect conversion of extracted components (hydrolysed carbohydrates, lipids and proteins) into bioplastic precursors via biochemical processes (e.g., the fermentation of extracted sugars to produce PHAs or lactic acid) [71]. A variety of enzymatic or catalytic chemical processes and hybrid routes can be employed for the polymerization of lactic acid, lipid-based and protein-based monomers [54,71–73]. Moreover, plasticisation, blending, and compatibilisation processes may be performed [54,74]. For example, PHA-, protein-, and starch-based blending is a simple approach to improve the characteristics of polymeric materials [75,76]. The most commonly used method to produce microalgae-polymer blends is compression moulding [74].

The selection of the most appropriate bioprocessing route and technologies depends on the desired product and the characteristics of the microalgal biomass. Several methods have been proposed to optimise the production process of various co-products and maximise the value derived from microalgal bioprocessing. This approach is known as the microalgal biorefinery concept, which enhances process viability by enabling the production of a wide range of marketable energy carriers and bioproducts with a zero-waste strategy in extraction and processing [4]. However, transitioning to mass-scale applications of microalgal biorefining is a paradigm shift that may take several years and require substantial investments to penetrate the market. Moreover, the development of more efficient and greener techniques is essential to promote environmental sustainability [5].

2.2. Sustainability assessment for microalgal systems and bioproducts

In the context of microalgal cultivation and derived bioproduct systems, TEA and LCA are the primary tools used to evaluate the economic and environmental dimensions of sustainability, respectively.

LCA is a methodological framework to assess the environmental burdens associated with all the life cycle stages of goods and services, from raw material extraction to disposal. The goal is to identify and quantify the inputs and outputs (resource consumption and waste generation) and to assess the potential environmental impacts resulting from these flows. Product systems can be benchmarked, providing valuable insights to guide decision-making strategies and policies. LCA can be conducted using a range of commercial or open-source software packages, such as SimaPro, GaBi, Umberto, and OpenLCA, each offering distinct advantages and limitations [77]. Several standards and guidelines have been developed to ensure the consistency, reliability, and comparability of LCA studies. Among the most widely recognised are the ISO 14040 [78] and ISO 14044 [79] norms, which provide the fundamental principles and guidelines for conducting LCA. According to them, the LCA methodology is structured into four interlinked analysis stages: goal and scope definition, inventory, impact assessment, and interpretation. It is important to note that LCA is an iterative process, meaning that findings obtained at any stage may necessitate revisiting and refining previous steps to improve accuracy and relevance.

TEA is a comprehensive methodology used to evaluate the economic viability of a technology, process, or product. By integrating technical assessments with economic analysis, TEA provides a holistic view of a project's feasibility and potential profitability, serving as a decision-support tool for system operation, design, scale-up, and investment planning [10]. Although several organisations have published guidelines and best practices that can be tailored to specific applications, no universally standardised framework for TEA currently exists. Nonetheless, in analogy with LCA [80], the TEA methodology can be structured with the four phases of goal and scope definition, inventory, economic assessment, and interpretation. Details on TEA methods can be found elsewhere [81,82].

3. Methodology

3.1. Search method and results

Two separate Boolean queries were used to capture recent review articles that include economic and environmental aspects of microalgal systems, as outlined in Table 1. Records were sourced from the Scopus database (Elsevier B.V.) and exported to a spreadsheet (Microsoft Excel®) to track the inclusion and exclusion of studies. To conduct the screening and selection process, the retrieved search documents were exported and managed using the Mendeley Desktop v.1.19.8 software (Mendeley Ltd, Elsevier B.V.).

The selection process was conducted according to the guidelines outlined in "Preferred Reporting Items for Systematic reviews and Meta-Analyses" (PRISMA) [83]. A flow diagram is illustrated in Fig. 3 with the adopted phases of i) identification of the records and ii) screening of the records/reports. Out of the 99 records initially identified, 14 duplicates were removed. A two-tier screening process was then conducted to identify review studies that satisfied the predefined eligibility criteria:

i. Topical relevance – the study must focus on microalgae-based production systems and include economic or environmental (or both) aspects, aligning with the scope of the meta-review.
ii. Data quality and representativeness – the article must present quantitative data on economic and/or environmental performance metrics (e.g., production costs or other economic or financial indicators, GHG emissions or other environmental impact metrics, energy balances) that are representative of current research trends and suitable for comparative or integrative analysis.

In the first-level screening, the abstracts of the retrieved records were assessed based on the first eligibility criterion, resulting in the exclusion of 11 non-pertinent articles. In the second-level screening, the full texts of the filtered reports were analysed according to the second eligibility criterion, leading to the exclusion of 34 articles due to insufficient or non-significant data. This process yielded a final portfolio of 40 eligible studies. The authors conducted the screening independently but reached joint decisions on article exclusion.

No formal quality assessment tool (e.g., AMSTAR-2) was applied to the included reviews. Given the exploratory and integrative nature of this meta-review, the selection focused on topical relevance and data usefulness rather than standardised methodological scoring. The available tools are widely used in medical and health sciences; hence, adapting them to the context of techno-economic/environmental research may require careful consideration and potentially necessitate the development of tailored criteria or modifications to the existing framework.

3.2. Review of the selected articles, classification of the case studies, and data analysis

The analytical review was organised with an initial screening focused on a detailed article-by-article examination and synthesis of the selected review studies, extracting representative "raw" data and

Table 1
Features of the search protocol applied to identify the review studies to be potentially included in the meta-review.

Feature	Description
Search query	Query #1: (microalgae) AND (economic analysis OR TEA) Query #2: (microalgae) AND (life cycle assessment OR LCA)
Search fields	Title, abstract, keywords
Temporal range	2023–2024
Document type	Review articles only
Database	Scopus (Elsevier B.V.)
Search date	26th April 2024

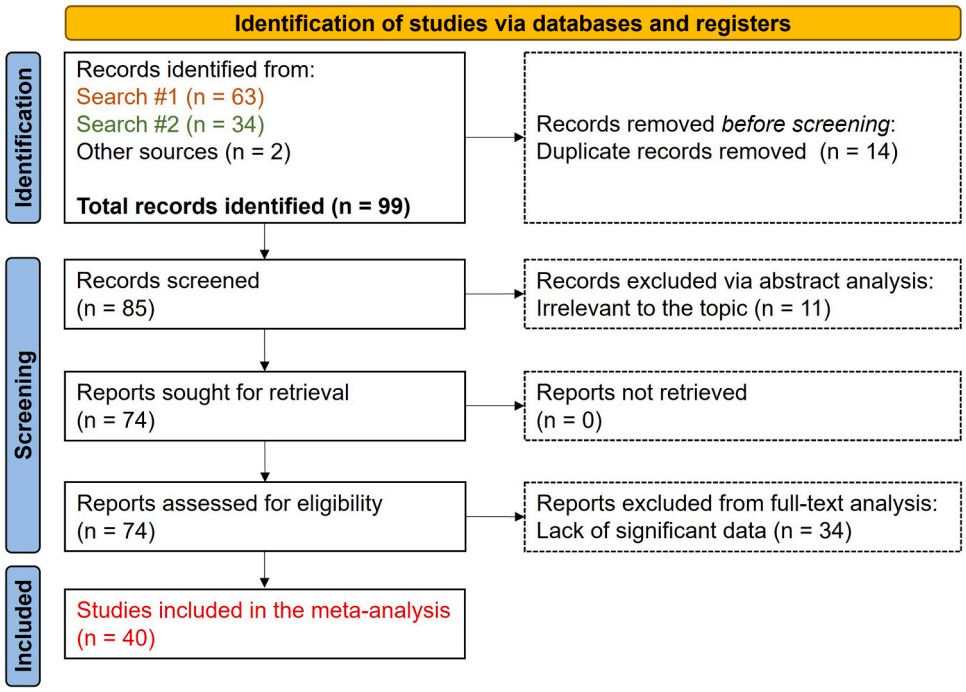

Fig. 3. Flow diagram, based on the PRISMA template [83], depicting the search and selection process for identifying the studies included in the meta-review. "Search #1" and "Search #2" refer to the queries described in Table 1; "Other sources" refers to review studies erroneously classified as research articles in the database.

highlights (Section 4.1.1). Note that the results reported by the analysed studies exhibited huge heterogeneity. On one hand, this was due to the intrinsic nature of our wide-spectrum search, which encompassed economic and environmental aspects and did not pose any restrictions in terms of microalgal products and technologies. On the other hand, inconsistencies in data presentation across the reviewed studies contributed further to this heterogeneity. Data were reported in the form of ranges or as single values, sometimes even without indicating the specific final product (e.g., generic references to "microalgal biofuels"); different metrics (e.g., cost and environmental impact per unit mass, volume, or energy content) and units were used, and/or case studies with various (multi-product) process schemes were included, producing an additional layer of variability. To organize and present all the retrieved data in this meta-review, the case studies were classified according to the target classes of bioproducts, namely biomass, biofuels, and biocompounds (Sections 4.1.2, 4.1.3, and 4.1.4, respectively), as well as the most promising strategies for performance improvement (Section 4.1.4, in which duplicated results from different reviews were removed). When relevant information was available in the reference source, the specific final bioproducts (distinct biofuels and biocompounds) were identified for each case study (Sections 4.1.3, 4.1.4, and 4.1.5). The data were homogenised to enable consistent reporting of the selected economic and environmental performance indicators in graphical form, allowing for a synoptic overview that supports a well-structured discussion and the definition of the key trends. Energy consumption, currency, and GHG emissions were homogenised in kilowatt-hours (kWh), US dollars ($) and kilograms of CO_2 equivalent (kg $CO_{2,eq}$), respectively. The functional units adopted were 1 kg of dry-weight biomass, 1 GJ of biofuel, and 1 kg of biocompound (e.g., lipids, proteins). For biofuels, the Net Energy Ratio (NER) was defined as the ratio of energy produced over energy consumed (so that values higher than 1 were considered desirable). Relevant benchmarks on conventional products were included to facilitate comparative analysis.

As a result, the systematic meta-review produced a narrative research synthesis [84], alongside the extraction, harmonisation, and interpretation of quantitative data, leading to the identification of several key implications for future research.

3.3. Limitations of the study

The limitations of the present meta-review are listed below.

- Search strategy and included reviews' quality: Our search was confined to a short publication window (a couple of years), and, due to the lengthy data-analysis and manuscript-preparation process, the dataset could not be updated at the time of submission. Therefore, we may have missed some older or very recent relevant reviews. Moreover, like any meta-review, our conclusions are inevitably affected by the quality of the selected reviews (which, for example, may vary in terms of risk of bias or methodological rigour). In this regard, we have not restricted our search to systematic reviews on TEA and/or LCA of microalgal systems and thus also included reviews that rely on a small number of primary studies. However, we believe this broader approach does not undermine the validity of the study's main conclusions, particularly in identifying prevailing trends.
- Heterogeneity across reviews and primary studies: The selected reviews used varying inclusion criteria and data reporting (e.g., ranges or multiple single data points), and the case studies exhibited a great variety of process conditions (algal species, bioreactor, cultivation mode, downstream steps, plant size, plant location, process scheme, bioproduct(s), energy sources, water and nutrient provision, use of wastewater and/or off-gas…) and modelling methodologies and assumptions (e.g., system boundary, multifunctionality treatment, impact assessment method, economic indicators, and measurement units). These heterogeneities entail limitations in synthesising results and hinder a full comparative analysis. Moreover, due to space constraints – given the large number and diversity of case studies – and because in-depth analysis of every primary source lies beyond the scope of a meta-review, we cannot present details for each case study. However, (i) where appropriate information was available in the source reviews, the specific final bioproducts were identified for each case study regarding biofuels or biocompounds, and (ii) additional important features were specified for a substantial

representative subset of studies grouped by the main strategic approaches documented for improved sustainability.

- Lack of granular data: The analysed reviews rely partially on aggregated or generalised data, such as broad value ranges or diverse bioproducts lumped under a generic label (typically "biofuel"), preventing, in some cases, detailed process- or product-specific insights. However, the source reviews reported most data as individual data points and documented many case studies on specific bioproducts (see previous point).
- Duplication and overlap: We observed a recurrence of some individual case studies across the included reviews. However, the extent of overlap was marginal, suggesting a low risk of bias in identifying key trends and drawing overarching conclusions.
- Overreliance on summary metrics: Focusing on pooled effect sizes or broad evidence grades can obscure important nuances, such as contextual factors, implementation challenges, and real-world applicability. To counter this, we enriched our study with dedicated sections on (i) future directions in sustainability assessments and (ii) a detailed SWOT analysis, which surface these subtleties and support their translation into practical strategies.
- No statistical treatment of data: We did not perform a statistical meta-analysis, resulting in a less robust quantification of average outcomes. However, this choice avoids statistical pitfalls and the risk of overstating effect magnitudes. Instead, we have classified the case studies, harmonized all data to uniform measurement units, and reported the results in charts to map semi-quantitative trends.

4. Sustainability of microalgal production systems and bioproducts

4.1. Meta-review of recent studies

4.1.1. Analysis of the review articles

Table 2 summarizes recent research trends and results on the economic and environmental sustainability of microalgae-based industries, as reported in the selected review articles. The majority of data pertain to the production costs and GHG emissions of microalgal biomass and its derived products, as assessed through TEA and LCA studies, respectively. Unfortunately, the results from the examined literature are notably heterogeneous. While many TEAs and LCAs have revealed the limitations of microalgal systems and the uncompetitiveness of microalgal bioproducts, several case studies have exhibited promising outcomes. As a result, the overall sustainability of the microalgal industry can still be considered uncertain.

4.1.2. Biomass

Navigating through Table 2, it can be observed that microalgal biomass cultivation is often affected by the critical hotspots of electricity demand (aeration, lighting, thermoregulation, and dewatering) and chemical nutrient consumption, which may result in high costs and environmental impacts. Nonetheless, some studies have reported more favourable outcomes. Overall, the material and energy inputs and the economic and environmental performance indicators are scattered over several orders of magnitude.

In this regard, Fig. 4 presents the values of energy consumption, production costs, and GHG emissions extracted from the analysed review studies. The figure reveals that energy consumption for microalgal biomass production varies from ~1 kWh/kg (dry-weight biomass) to hundreds of kWh/kg. Xu et al. [2], for example, reported a range of 0.33–234 kWh/kg, whereas Smetana et al. [117] mentioned three values exceeding 200 kWh/kg. Regarding pilot-scale studies based on primary data, variable estimations were documented, albeit with a predominance of values clustered around 100 kWh/kg [56].

Assuming an electricity price of 0.1–0.2 $/kWh [118,119], energy consumption alone would result in high operational costs, i.e., in the order of 10^1 $/kg. This rough estimate aligns approximately with the

Table 2
Representative "raw" data (no homogenisation of units) and valuable insights on economic ($) and environmental (♣) aspects from recent review articles on microalgal systems. Part of this table was published in a previous work [85].

Title	$/♣	Main data	Highlights	Ref.
The application of magical microalgae in carbon sequestration and emission reduction: Removal mechanisms and potential analysis	$	Biomass production costs of ~58 and 400 $/ton were reported, the former along with a payback time of 2.81 y. Biodiesel production from microalgae cultured in domestic wastewater was viable with a return on investment (ROI) of 41 % and a payback period of 2 years. By comparing the break-even costs of six conventional carbon sequestration techniques, the microalgal pathway had good prospects and economic feasibility (230–920 $/tonne CO_2).	Efficient cultivation bioreactors (combining suspended and attached systems), wastewater and exhaust gas treatments, and multi-product biorefinery were prospected as key factors to improve the economic feasibility of the microalgal industry.	[1]
Scale-up of microalgal systems for decarbonization and bioproducts: Challenges and opportunities	$	Microalgal carbon capture was not profitable due to the high energy consumption (values spread over the 0.33–234 kWh/kg biomass range), which was associated with large amounts of indirect emissions (~1 kg $CO_{2,eq}$/kWh). The market price of branded microalgae-derived products was ~300–800 $/kg for various antioxidants and ~20–100 $/kg for microalgae powder/tablet. Several recent studies showed that the biomass cost varied from 0.59 $/kg to 25.07 $/kg, with most values being below 10 $/kg. Flat panel PBR and ORP systems (~3.4 $/kg biomass) outperformed tubular systems (~5.1 $/kg). The unit cost values for lipid production were 5.4–8.3 $/kg, depending on the microalgal species. However, one case study reported a	Beyond reducing energy demand, microalgal industries must rely on multi-product valorization to be profitable. However, high costs, low yields, and immature technologies challenge economic viability. Major cost drivers for biomass production include capital investment, energy use, or labour.	[2]

(continued on next page)

Table 2 (*continued*)

Title	$/♣	Main data	Highlights	Ref.
		minimum lipid selling price of 1.8 $/L. A minimum diesel selling price of 1.85 $/L and a cost of biocrude of 0.96 $/L were also reported.		
Upcycling food waste into biorefinery production by microalgae	$, ♣	The nutrients and freshwater used for cultivation can constitute 20 %–30 % of the total cost of the process. Food wastewater reduced the costs by as much as 50 % while saving ~90 % of freshwater. The energy demand values were 4181.3, 1516.2, and 217.1 MJ/kg protein for ORP, tubular PBRs, and heterotrophic fermenters, respectively, and the global warming potential was ~245, 96, and 15 kg $CO_{2,eq}$/kg protein, respectively. Closed-loop wastewater cultivation led to a ~10 % reduction of the total cost and a 50 % reduction in the global warming potential. Lipid and astaxanthin costs decreased from 9.43 and 4345 $/kg to 7.59 and 3345 $/kg, respectively, for a fed-batch culture. Mixotrophic conditions reduced global warming and biofuel costs by up to ~75 %. Microalgae harvesting typically had an incidence of ~20 %–30 % on the total production costs.	Integrating algal cultivation with food wastewater treatment is an effective strategy to improve the economic and environmental viability of algae-derived products.	[86]
Sustainable hydrogen production via microalgae: Technological advancements, economic indicators, environmental aspects, challenges, and policy implications	$, ♣	A closed pond and a helical PBR were characterised by minimum selling prices of biomass of 2869 $/ton and 921 $/ton, respectively, and by global warming potentials of 339 g $CO_{2,eq}$/MJ and 9.1 g $CO_{2,eq}$/MJ, respectively. Microalgal-derived biohydrogen exhibited a minimum fuel selling price (MFSP) of 37–52 $/GJ. The results of another study showed a payback period of 3.78 years and an internal rate of return (IRR) of 22 %, while the global warming potential was 7.56 kg $CO_{2,eq}$/kg H_2 (which was 37 % lower than that of steam methane reforming). Another TEA reported a total cost of hydrogen of 10 $/GJ, with a high incidence of capital expenditures (up to 90 %).	Biomethane production was not economically feasible. Biohydrogen was competitive with current technologies.	[87]

Table 2 (*continued*)

Title	$/♣	Main data	Highlights	Ref.
Photobioreactor configurations in cultivating microalgae biomass for biorefinery	$	The unitary costs of biomass and biofuels were ~105 €/kg and 6 $/gal, respectively. A profitable production of dried *Spirulina* food was characterised by a total cost of 8.55 million €/y and revenues of 21.45 million €/y.	Seven TEA studies were compared.	[23]
A review of the strategy to promote microalgae value in CO2 conversion-lipid enrichment-biodiesel production	$, ♣	A cost of microalgal biodiesel of 0.33 €/L and an investment recovery period of 5–10 years were recorded, thanks to the economic value of residual biomass and glycerol by-products. Considering the economic conditions of Guinea-Bissau, a study estimated a biodiesel cost of 0.9 $/kg. The other economic data were a cost of biomass production in the 150–6000 $/ton range, and a cost of lipids of 7.5 $/kg or 480 $/kg for heterotrophic and phototrophic cultivation, respectively (the latter being affected by a higher water and energy consumption). Triglycerides costs were reported at 8.52 $/gal for ORPs and 18.10 $/gal for PBRs. The 5–22 $/gal range was mentioned for the biodiesel cost.	Despite lab-scale progress, microalgal biodiesel faces key sustainability challenges. While wastewater use and supercritical conversion offer environmental benefits, solvent-based lipid extraction can cause significant impacts.	[88]
Insights into renewable biohydrogen production from	$	De-oiled microalgal biomass was evaluated at 100–225 $/ton.	Microalgal biohydrogen showed competitiveness	[89]

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Table 2 (*continued*)

Title	$/♣	Main data	Highlights	Ref.
algal biomass: technical hurdles and economic analysis		However, utilising the leftover biomass for biohydrogen production could produce an extra credit of 0.95–2.43 $/gal biohydrogen, thereby resulting in a reduction of the de-oiled biomass price to 28.5 $/ton. The microalgal biohydrogen production cost was ~10–20 $/GJ.	with the current technologies. Bioreactor optimization, process integration, and the TEA of large-scale applications were identified as key factors.	
Advances in microalgae-based carbon sequestration: Current status and future perspectives	$, ♣	The market value of proteins, lipids, carbohydrates, and carotenoids was around 0.20, 0.41, 0.10, and 115 $/g, respectively, and the microalgal product market was projected to grow from 11.8 billion to 25.4 billion $ by 2033. A company generated 1147 MWh/y of photovoltaic energy (1.3-acre solar panel array, in a microalgae cultivation area of 90 acres), thereby reducing GHG emissions by 791 ton/y.	Across seven studies, *Dunaliella salina* emerged as the most profitable species. A couple of LCA studies showed electricity demand as a major emission source, with renewables potentially reducing emissions by up to 99 %.	[3]
Innovative Bioactive Products with Medicinal Value from Microalgae and Their Overall Process Optimization through the Implementation of Life Cycle Analysis—An Overview	♣	The production of PUFAs from heterotrophic algae was affected to a great extent (65 % of GHG emissions) by the cultivation of sugar cane (substrate). Extraction solvents (particularly chloroform) and electrical energy were the most important impact drivers. A comparative LCA estimated environmental benefits when chloroform was substituted with hexane, but microalgae-derived ω−3 fatty acid (eicopentaenoic acid, EPA) production at the pilot scale was significantly affected by energy demand, transportation and provision of nitrogen-based nutrients.	β-carotene extraction from *D. salina* exhibited higher impacts than carrot-based farming, mainly due to energy-intensive drying. Ultrasound-assisted extraction was recommended. Other studies identified supercritical CO_2 and CO_2-expanded fluid extraction as greener than organic solvents, though renewable energy is needed to optimise the environmental footprint. Various strategies (metabolic engineering, strain adaptive evolution in a high-salinity medium, and adding a food-waste hydrolysate) can effectively reduce the environmental impacts of EPA. For astaxanthin, bacterial bioconversion and	[90]

Table 2 (*continued*)

Title	$/♣	Main data	Highlights	Ref.
		In astaxanthin production, the microalgal cultivation stage was the most energy-intensive one, due to the use of artificial light. In phycocyanin extraction, dried biomass provided a higher yield and lower impact than wet biomass.	chemical synthesis outperformed the microalgal route.	
Emerging Sustainability in Carbon Capture and Use Strategies for V4 Countries via Biochemical Pathways: A Review	♣	Bio-oil production from microalgal fermentation was dominated by nutrient and electricity demands, accounting for 86 % of environmental impacts. Biohydrogen and biomethane production consumed ~54 % and 17 % of the energy during biomass pre-treatment and cultivation. The GHG emissions totalled 124 g $CO_{2,eq}$/MJ, primarily due to electricity (~42 %). Using wastewater instead of synthetic nutrients in HTL-based bio-oil production reduced GHG emissions from 4.7 to 0.233 kg $CO_{2,eq}$/MJ. The GHG emissions of syngas production ranged from 70 to 195 g $CO_{2,eq}$/MJ, but a solar drying system reduced them to below 40 g $CO_{2,eq}$/MJ.	The environmental impact of microalgal biofuels and pigments surpassed that of fossil-derived fuels and synthetic pigments. Impacts can be greatly reduced by harnessing sunlight and integrating microalgae cultivation with wastewater treatment. GHG emissions of microalgal syngas can compare favourably with steam methane reforming (~100 g $CO_{2,eq}$/MJ).	[91]
Abiotic stress as a dynamic strategy for enhancing high-value phytochemicals in microalgae: Critical insights, challenges and future prospects	$	Biomass conversion into valuable biochemicals was affected by cultivation costs of 0.5–6 $/kg. ORPs were cheaper than closed PBRs, but yielded lower bioactive compound content (e.g., astaxanthin in *H. pluvialis* <3 % vs. >4 %). Astaxanthin production cost was 7000 $/kg. The payback period for protein, fatty acid, and pigment production was 2.62 y, while it was	Infrastructure, maintenance, and labour were the primary cost drivers in microalgae cultivation. Astaxanthin production was inefficient and uncompetitive (vs. 1000 $/kg in chemical synthesis). The economic viability can be significantly improved in multi-product biorefineries.	[92]

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Table 2 (*continued*)

Title	$/♣	Main data	Highlights	Ref.
		6.38 y for proteins alone. Other economic indicators were: an ROI of ~38 % for the abovementioned multi-product scheme; an ROI of 1.87 % and payback time of 11 y in another protein production TEA; a β-carotene price of either 1370 or 920 €/kg.		
Microalgal protein for sustainable and nutritious foods: A joint analysis of environmental impacts, health benefits and consumer's acceptance	$, ♣	The total production costs were 100 $/kg for *Haematococcus pluvialis* (cultivation cost of 14–18 $/kg), 3.4 €/kg for a large-scale cultivation system in Spain, and 4 $/kg for *Spirulina*. Cell disruption would add ~0.5 €/kg, while extraction and purification of soluble protein could add 4.5–13 €/kg. Microalgal protein costs ranged from 10 to 18 €/kg. Protein-rich and carbohydrate-rich microalgal feedstocks were priced at 0.75 and 1.1 $/kg, respectively. With a market value of ~30–100 $/kg in the supplement market, PUFAs can represent a lucrative opportunity. Carotenoids were valued between 32 and 1200 $/kg. Different microalgae cultivation systems exhibited mean values of GHG emissions ranging from 95 to 195 kg $CO_{2,eq}$/kg protein.	The yield of microalgal protein was relatively low, and its cost was higher than that of proteins derived from yeast or fungi using cellulose-containing residues (5–9 €/kg). Microalgal cultivation consumed more energy and caused greater environmental pressure than plant protein, but its impact was comparable to that of animal protein	[93]
Life cycle assessment with the transition from lignocellulose- to microalgae-based biofuels: A review	♣	Producing 1 kg of microalgal biodiesel required 3726 kg of water, 0.71 kg of P, and 0.33 kg of N, but reusing harvested water could reduce water and nutrient use by 84 % and 55 %, respectively.	Microalgal biodiesel production was limited to lab- and pilot-scale studies, and the associated LCAs were not considered comprehensive. It was claimed that microalgal biofuels required less land and fewer resources than first- and second-generation biofuel sources. However, various limitations hinder the commercialisation of such systems. The energy balance was compromised by the significant power demands during production, harvesting and oil extraction.	[94]
Sustainable point of view: Life cycle analysis for green extraction technologies	♣	The GHG emissions were 1.86 t $CO_{2,eq}$/800 g astaxanthin, 0.33 kg $CO_{2,eq}$/MJ biodiesel, 0.6 kg $CO_{2,eq}$/kg biodiesel, ~500 kg $CO_{2,eq}$/kg β-carotene, ~1000–2000 or 140 kg $CO_{2,eq}$/kg phycocyanin when ultrasound or pulsed electric field extraction was used, and 9.09 kg $CO_{2,eq}$/kg *Schizochytrium* oil. Cultivation and lipid extraction required ~36 % and 56 % of energy, respectively. Using pure CO_2 increased GHG emissions and energy consumption by 25–30 % compared to waste CO_2.	Green techniques (supercritical fluid, pressurised liquid, ultrasound, microwave, pulsed electric field) for metabolite (phycocyanin, carotenoids…) extraction reduced environmental burdens, compared to conventional methods. Limited data from large-scale plants and reliance on lab-scale results introduce inaccuracies into LCA outcomes.	[77]
Microalgae-based technologies for carbon neutralization and pollutant remediation: A comprehensive and systematic review	$, ♣	Wastewater treatment reduced nutrient cost from 1605.9 JPY/kg biomass to 160.6 JPY/kg biomass. High-rate algal ponds (HRAP) had a lower treatment cost than that of sequencing batch reactors (SBRs) (0.18 vs. 0.26 €/m^3) as well as lower environmental impacts (0.146 vs. 0.458 kg $CO_{2,eq}$/m^3 for GHG emissions, and 126 $\times 10^{-6}$ vs. 158 $\times 10^{-6}$ kg $PO_{4,eq}$/m^3 for eutrophication). The carbon capture cost was 702–1585 $/ton net CO_2 sequestered, and the corresponding carbon removal efficiency was 73–51 %. The microalgal biodiesel cost was 1.7–2.0 $/kg.	Incorporating carbon capture and wastewater treatment into microalgal biofuel production could yield economic and environmental benefits. Wastewater treatment costs could be reduced, and expenses for fertilisers and freshwater in microalgae cultivation could also be lowered.	[95]
Comparative study on conventional and microalgae-based air	$, ♣	Biomass production costs were 2.29 $/kg for a bubble column PBR and	Detailed TEA or LCA data on the Microalgal Air Purification	[96]

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Table 2 (*continued*)

Title	$/♣	Main data	Highlights	Ref.
purifiers: Paving the way for sustainable green spaces		2.82–25.07 $/kg for a flat panel PBR. The other data included a biomass cost of either ~600 $/t or 480–1025 $/t, and a biofuel cost (from HTL) of ~7 $/gal.	Technology (MAPT) were not available. Energy consumption for thermoregulation, aeration, lighting and/or drying was an environmental hotspot. The authors concluded by claiming that conventional air purifiers provided better efficiency at cheaper costs, while the emerging MAPT had a lower environmental impact.	
Realization process of microalgal biorefinery: The optional approach toward carbon net-zero emission	$, ♣	Different PBR systems were characterised by significantly diverse costs, ranging from 2.82 to 30.97 $/kg. Using waste resources for nutrients and flue gas for the CO_2 supply could reduce lipid production costs by 36–95 %. NER (defined as energy consumed over energy produced) and GHG emissions of 1.23 and –11 g $CO_{2,eq}$/MJ, respectively, were reported for microalgal bioenergy production through HTL, which outperformed pyrolysis. Microalgal biorefineries showed low impacts on eutrophication, land use, soil acidification, and human toxicity.	The simultaneous synthesis of value-added products was the most cost-effective method to enhance the commercial feasibility of microalgal biorefineries. Although the commercial returns were still unsatisfactory, novel microalgal biorefinery schemes were claimed to be a promising strategy for environmental sustainability. Culturing microalgae in wastes could significantly reduce the total expenditure of production. Integrating wastewater and flue gas had the potential to reduce the environmental impacts of cultivation in PBRs, but the high energy consumption for artificial illumination and aeration is an issue to be solved.	[97]
Microalgae as tools for bio-circular-green economy: Zero-waste approaches for sustainable production and biorefineries of microalgal biomass	$, ♣	Jet biofuels had a minimum sale price of 5.89 $/L, 14 times higher than fossil-based jet fuel. Using volatile fatty acids from food waste fermentation as a nutrient source for the heterotrophic growth of microalgae improved lipid yield and reduced biodiesel	The valorisation of liquid and solid waste from microalgae cultivation or other sources could reduce costs and environmental impacts. Using wastewater was recognised as an established method to reutilise nutrients and water, thereby reducing environmental	[98]

Table 2 (*continued*)

Title	$/♣	Main data	Highlights	Ref.
		production cost to 2.3 $/gal.	impacts. Mixotrophic cultivation is another key approach for microalgal biorefineries because it can boost microalgal biomass productivity, the CO_2 fixation rate and lipid accumulation.	
Extraction methods of algae oils for the production of third-generation biofuels – A review	$	Microalgal lipid extraction was too costly, making up to 50 % of the biodiesel production cost. MFSPs were 4.85 $/L biocrude and 5.57 $/L biodiesel. The extraction of 1 kg lipids required hundreds of kilograms of solvents, which determined a cost contribution of ~1000 $/kg lipid or even more when green solvents were used. Lipid extraction incurred energy consumption costs of ~10–40 $/kg.	Biocrude and biodiesel were uncompetitive with conventional diesel (1.59 $/L). The primary expense of solvent-based extraction methods came from the purchase of chemicals. Supercritical CO_2 extraction was the cheapest method	[99]
Microalgae-assisted green bioremediation of food-processing wastewater: A sustainable approach toward a circular economy concept	$	The market value of high-purity chemicals was as high as 27 $/mg phycocyanin, 3.71 $/mg astaxanthin, 17 $/g β-carotene, 2.5 $/mg lutein, 650 $/kg EPA, and 50 $/kg docosahexaenoic acid (DHA). Biodiesel costs of 2.29 $/kg and 3.9 $/L were reported. Astaxanthin co-production or cultivation in wastewater reduced the biodiesel cost to 0.54 $/L and 0.73 $/kg, respectively. The microalgal bioethanol break-even price was 2.61 $/kg.	Biodiesel production was uncompetitive (vs. 1.08 $/kg petroleum diesel), but astaxanthin co-production and cultivation in wastewater were cost-effective approaches. Microalgal bioethanol was not viable (market price of 1.66 $/kg).	[100]
Strategies and challenges to enhance commercial viability of algal biorefineries for biofuel production	$, ♣	An MFSP of 4.3 $/GGE (gasoline gallon equivalent) was reported for biofuel (gasoline, jet fuel, diesel, and H_2) from algae cultivated in wastewater. The microalgal product market was valued at 2.36 billion $, with an	Algal biorefinery startups were described. LCA studies led to a wide variety of results.	[101]

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Table 2 (*continued*)

Title	$/♣	Main data	Highlights	Ref.
		estimated increase to ~4 million $ by 2027. One company produced biofuels at 1.30 $/gal from a genetically modified algal strain. Algal biofuel required fossil energy ranging from 3.6 to 5.7 MJ/kg and produced GHG emissions of 0.85–1.46 kg $CO_{2,eq}$/kg biodiesel. Another study reported 85.37 g $CO_{2,eq}$/MJ, and an output over input NER of 0.45. Carbon credits (GHG emissions of –1.11 kg $CO_{2,eq}$/kg algae) were estimated in another LCA.		
Transition from synthetic to alternative media for microalgae cultivation: A critical review	$	The cost of a synthetic growth medium (BG11) was 0.328 $/L, while alternative media (wheat bran + garlic powder) were much cheaper (0.018 $/L), significantly reducing biomass production costs. Fogg's medium cost was ~0.04 $/L, while the cost of cow urine was only 0.025 $/L. Using recycled media reduced costs by 37.5 % compared to synthetic Chu medium.	Several studies showed a significant economic benefit of using alternative cultivation media.	[102]
From anaerobic digestion to single cell protein synthesis: A promising route beyond biogas utilization	$	The production cost of single-cell protein from microalgae was 1.4–1.9 €/kg. *Chlorella* and methane-oxidising bacteria were used to treat liquid digestate, and an income was achieved in the biogas conversion pathway with a 30-fold increase in single-cell protein production, compared to the electricity pathway.	While not yet fully cost-competitive with conventional proteins in all sectors, microalgal single-cell protein can take advantage of co-product valorization.	[103]
Global Perspective of Hydrothermal Liquefaction of Algae: a Review of the Process, Kinetics, and Economics Analysis	$	The MFSP and the overall exergy efficiency varied widely over the 1.70–22 $/GGE and 20–96 % ranges, respectively.	The great variability of results was attributed to various factors, such as feedstock price, scale of operation, yield and quality of the biocrude. HTL technology has not yet reached commercial scale and requires techno-economic optimisation and pilot-scale studies. Exergy analysis was recommended as a valuable tool for developing sustainable biocrude production alternatives.	[104]
Biofuel production from microalgae: challenges and chances	$, ♣	The cost of microalgal bio-oil varied widely over the 0.44–8.76 $/L range. Wastewater could save up to 90 % of freshwater and minimise the reliance on chemical nutrients.	Microalgal bio-oil was uncompetitive with conventional fuels. Only a few pilot projects have been realised, while several obstacles, resulting in high operation and capital costs, still hinder the scaling up and commercialisation of microalgal biofuels. Cultivating microalgae in wastewater can improve biofuel sustainability compared to traditional crop-derived fuels.	[105]
Unlocking the potential of microalgae bio-factories for carbon dioxide mitigation: A comprehensive exploration of recent advances, key challenges, and energy-economic insights	$, ♣	A life cycle energy assessment comparing an open pond, a tubular PBR, and a bubble column PBR showed the bubble column PBR as the best option due to low energy demand and high productivity. Another assessment found that natural lighting saved 57 % of energy compared to artificial lighting for microalgae cultivation in activated sludge. Purchasing a glass tube cultivation system accounted for 24–31 % of total investment costs, followed by the drying system (21–24 %) and building construction (18–21 %). Another study found that the solid-liquid separation represented 20–30 % of total capital costs.	The feasibility of microalgal systems is uncertain, with energy consumption being critical due to multiple energy-intensive steps. Challenges with scaling up and capital costs also persist.	[106]

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Table 2 (*continued*)

Title	$/♣	Main data	Highlights	Ref.
Production of sustainable biofuels from microalgae with CO2 bio-sequestration and life cycle assessment	$, ♣	The biomass production cost of flat panel PBRs, horizontal tubular PBRs, and ORPs (including dewatering) was 5.96, 4.15, and 4.95 €/kg, respectively. However, the minimum cost for optimised systems was 0.68 €/kg. Mixotrophic growth led to ~0.9 $/kg. A biomass production cost of 69 €/kg was caused mainly by depreciation and labour. Simplifying the technology and scaling up could cut production costs to 12.6 €/kg. Using volatile fatty acids from waste food in heterotrophic cultivation boosted lipid yields and reduced biodiesel costs to 2.3 $/gal.	The LCA debate on microalgal biofuels focused on the impacts of large-scale generation, particularly on inorganic salts, energy inputs, water use, chemical fertilisers, methanol use for transesterification, and glycerol by-products yield. A selection of ten studies showcased diverse methodologies (functional unit, multi-product treatments, system boundaries, software, and sensitivity analyses).	[107]
Microalgal biofilms: Towards a sustainable biomass production	$	Microalgal biofilm achieved higher biomass productivity and cut harvesting energy use by up to 83 %. A preliminary TEA using small-scale outdoor data reported biofilm-based biomass costs (e.g., ~1 vs. 10 $/kg) 8–10 times lower than suspension-based, thanks to higher productivity and reduced water, energy, and lower labour inputs.	Microalgal biofilm outperformed conventional suspended cultivations. However, several technical limitations hinder biofilm-based algae cultivation on a large scale.	[108]
Recent advances in CO_2 fixation by microalgae and its potential contribution to carbon neutrality	$, ♣	PBRs and ORPs had biomass production costs of 12.4 and 1.6 $/kg, respectively, largely driven by facility investment (2000 and 50 $/m^3 for PBRs and ORPs, respectively). Algal protein production cost exceeded 10 $/kg but fell to 0.43 $/kg when co-producing biodiesel, which added 0.97 $/kg in revenue. Extracting the protein before lipid separation yielded a revenue of 6.23 $/kg. Low-value biofuel could be produced	Scientific research is driving the industrialisation of microalgal systems, but (i) the high cost of cultivation infrastructures and nutrients and (ii) licensing for marketing bioproducts remain great challenges. Biorefineries could maximise the biomass value and offset the production cost of various products. Fossil-based electricity emerged as the primary driver of the global warming potential.	[109]

Table 2 (*continued*)

Title	$/♣	Main data	Highlights	Ref.
		at a low biomass cost of 0.20 $/kg by valorizing waste CO_2. GHG emissions varied widely – up to ~1000 kg $CO_{2,eq}$/kg biomass – and were influenced by cultivation technology and scale, process conditions and inputs (flue gas and nutrients), harvesting method, and microalgal strain. Energy usage ranged from 4 to 800 MJ/kg biomass.	Using renewable energy and waste nutrient sources (wastewater, waste gas, or food waste) effectively reduced environmental impact and could enable net carbon sequestration.	
Microalgal Feedstock for Biofuel Production: Recent Advances, Challenges, and Future Perspective	$, ♣	Several TEAs showed large variability in biofuel production costs, which were compared with commercial prices: 0.77 or 0.8–3.5 $/L vs. 1.15 $/L for biodiesel, 19.45 or 1.3 $/gal vs. 2.72 $/gal for bioethanol, 0.57–13.53 $/kg vs. 2–8 $/kg for biohydrogen, 0.55 or 0.3 $/m^3 vs. 0.25–2.7 $/m^3 biomethane, 2.2 or 0.7 $/L vs. 0.48–0.53 $/L for biocrude, 1.48–1.8 or 0.58 $/L vs. 0.71 $/L for pyrolysis oil, 5.89 or 8.45 $/L vs. 0.9 $/L for biojet fuel. CapEx accounted for 57–84 % of the production cost for most biofuels, while it was as low as 42 % for biocrude and 30 % for bioethanol. Values of NER (energy produced over energy consumed) < 1 were reported for bioethanol, biodiesel, biomethane and biocrude. Large-scale HTL biocrude and supercritical water-extracted biohydrogen both achieved NERs of 1.3, while pyrolysis-based bio-oil reached the highest value of ~2.2. GHG emissions ranged from	Data collection from large-scale plants (e.g., pre-commercial scale) is crucial to conduct realistic TEAs. Strain selection, harvesting optimisation and wet biomass processing will ultimately determine microalgal biofuel viability.	[110]

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Table 2 (*continued*)

Title	$/♣	Main data	Highlights	Ref.
		~1–7.5 kg $CO_{2,eq}$/kg biofuel – lowest for bioethanol and highest for biohydrogen. HTL and pyrolysis had the potential to be sustainable in terms of NER and GHG emissions.		
Advancements in Microalgal Biorefinery Technologies and Their Economic Analysis and Positioning in Energy Resource Market	$, ♣	Microalgae production cost values of 500–3500 $/t, 8.66–11 €/kg, and 4.75–6.55 $/kg were reported. The results included values of MFSP of 12.85 $/GGE, 10.41 $/GGE, 2.2 $/L, 1.17 $/LGE (litre gasoline equivalent), and 1186 €/t, which were associated with global warming potentials of 111.2 g $CO_{2,eq}$/MJ, –2 g $CO_{2,eq}$/MJ, –1.13 g $CO_{2,eq}$/MJ, 23 g $CO_{2,eq}$/MJ, and 26.6 g $CO_{2,eq}$/MJ, respectively. Biorefinery companies had a production throughput ranging from 100 million to 1 billion gal/y and a revenue of 93,000–16.8 M $/y. TEA and LCA results included a biodiesel cost of 1.75 $/L, with an NER (produced over required energy) of 0.76 and GHG emissions of –3.73 kg $CO_{2,eq}$/L, a biomass cost of 0.5 $/kg with emissions of 7.56 kg $CO_{2,eq}$/kg H_2 and 1.18 kg $CO_{2,eq}$/kg CH_4, a lower biofuel cost than 0.5 $/GGE, with lower emissions than 20 g $CO_{2,eq}$/MJ, an MFSP of 4.3 $/GGE, and an MFSP of 2.23 $/gal.	Several TEA and LCA studies assessed various biorefinery products. The environmental impacts were uncertain, and the poor performance was primarily due to the electricity demand. Capital expenditure was identified as the main challenge in biofuel production. International biorefinery companies were mentioned. TEA and LCA studies showed that integrating bioremediation (e.g., wastewater treatment) with microalgal cultivation enhanced sustainability, though further research is needed to confirm real-world applicability.	[111]
Biofuel production from Euglena: Current status and techno-economic perspectives	$	The tabulated data included an MFSP of 1.48–2.79 $/L biodiesel, a biomass production cost of 2.82–30.97 $/kg (*Chlorella vulgaris* in PBR), a minimum biomass selling price of 0.64–1.79 $/kg (*Scenedesmus* sp. in PBR), CapEx and OpEx of 351.2 and 322.5 $/t biomass (*Nannochloropsis salina* in ORP), respectively, a biodiesel production cost of 3.69 $/L, CapEx of 1.3 or 2 $/kg along with OpEx of 1.4 or 2.6 $/kg (*Tetraselmis suecica* in PBR). Heterotrophic cultivation reduced the production cost to 1.4 or 1.07–1.59 $/kg biomass. However, another study predicted CapEx and OpEx values of 0.89 and 3.11 €/kg biomass, respectively. A company invested 50 million $ to build an *Euglena*-based refinery. Using food by-products as a carbon and nutrient source, they expected to cut jet biofuel costs by up to ~0.89 $/L by 2025.	TEA results varied with microalgal species, cultivation system, and plant location. Heterotrophic cultivation could achieve higher biomass and valuable compound productivities than autotrophic methods. Jet biofuel cost was comparable to that of petroleum-based jet fuel cost (0.62 $/L).	[112]
From present to prosperity: assessing the current status and envisioning opportunities in the industrial-scale cultivation of Haematococcus pluvialis for astaxanthin production	$	Astaxanthin's market was projected to grow from 1 billion $ in 2019–3.4 billion $ by 2027 (compound annual growth rate, CAGR, of 16.2 %). The market value of *H. pluvialis*-based natural astaxanthin was forecasted to reach 148.1 million $ by 2027 (CAGR 13.2 %). The high cultivation cost of *H. pluvialis* accounted for ~20–30 % of the total costs (1669.87–6961.07 $/kg astaxanthin). Geographical locations with optimal light intensity and temperature could reduce *H. pluvialis*-based astaxanthin production costs to 1800 $/kg. The labour cost had a significant incidence, though with a great regional variability (e.g., ~120 $/kg in China and 600 $/kg in the USA). The production cost of *H. pluvialis* was 4.4–15.4 times	Natural astaxanthin has much higher antioxidant capacity than synthetic astaxanthin, but its competitiveness is limited by a selling price of ~5000 $/kg vs. 2000 $/kg for synthetic. A biorefinery approach was recommended to increase the process profitability of *H. pluvialis* (co-production of bioethanol, biodiesel and animal feeds). TEA studies are needed to evaluate the industrial production of astaxanthin, focusing on biorefinery routes and mixotrophic cultivations.	[113]

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Table 2 (*continued*)

Title	$/♣	Main data	Highlights	Ref.
		higher than the average cost of producing microalgal biomass.		
Recent Trends on Domestic, Agricultural and Industrial Wastewaters Treatment Using Microalgae Biorefinery System	$, ♣	HRAPs could cut wastewater treatment costs (0.18 €/m^3 vs. 0.26 €/m^3), global warming potential (0.146 vs. 0.458 kg $CO_{2,eq}/m^3$), eutrophication (126 $\times 10^{-6}$ vs. 158 $\times 10^{-6}$ kg $PO_{4,eq}^{3-}/m^3$), and reduce energy use by 78 % compared to conventional activated sludge systems. However, an activated sludge-based sequencing batch reactor provided superior nutrient removal. In biofuel production, co-pyrolysis of a 1:1 mixture of sewage sludge and wastewater-grown microalgae achieved the highest net profit, 9 % more than sludge alone, which, however, exhibited lower environmental burdens. The high moisture content made drying the most energy-intensive step (69–88 % of the total energy use). Replacing conventional cultivation media with wastewater can reduce environmental burdens by up to five-fold.	Integrating wastewater treatment is a successful method to improve the economic and environmental performance of microalgal systems.	[114]
A review on the current application of light-emitting diodes for microalgae cultivation and its fiscal analysis	$	The total cost of LED lighting for internally illuminated PBRs was ~14–15 $/kg biomass (at 0.11 $/kWh electricity), a ~40–50 % reduction compared to the results of a previous study, with lower investment and operating costs. Only ~6–8 % of electrical energy was converted into chemical energy (microalgal biomass).	Artificial lighting can represent a major cost driver in microalgal cultivation. Therefore, systems that utilize sunlight should be prioritized.	[115]
Life cycle assessment of bio-based nitrogen upcycling approaches	$, ♣	Using a food agro-industrial effluent for microalgal bioconversion into N-based fertilisers reduced the impacts of freshwater ecotoxicity (24 %), terrestrial ecotoxicity (26 %) and terrestrial acidification (69 %). The global warming potential was 115 kg $CO_{2,eq}$/kg recovered nitrogen. Wastewater treatment in HRAPs exhibited GHG emissions of 146 $\times$ 10^{-3} kg $CO_{2,eq}/m^3$ and life cycle costs < 0.2 €/m^3.	Wastewater treatment can improve the sustainability of microalgal systems.	[116]
Microalgae in Bioplastic Production: A Comprehensive Review	♣	PLA bottles lowered the global warming potential by 20 % and used two-thirds less energy than PET bottles. Among end-of-life options, biodegradation was preferred, while incineration, landfilling, and recycling were deemed unsuitable for bioplastics.	The strengths of bioplastic rely on the use of renewable raw materials and the elimination of toxic production processes.	[75]
Meat substitutes: Resource demands and environmental footprints	♣	Centrifugation and spray-drying accounted for over 70 % of total energy use (335 or 250 kWh/kg, depending on the algal species) after growth in ORPs. In contrast, closed PBR cultivation consumed 80 % of total energy (686 kWh/kg). GHG emissions of closed PBRs and ORPs were 220 and 141 kg $CO_{2,eq}$/kg *C. vulgaris*, respectively. Using slurry and wastewater reduced nutrient-related GHG emissions by 80 % and 20 %, respectively.	The environmental profile of microalgae cultivation was affected by the location, season, scale, algal species and nutrient source. Phototrophic systems were less productive than heterotrophic cultivations. Nutrient provision was a key factor that can be addressed using wastewater. The GHG emissions and non-renewable energy impacts of microalgae were significantly higher compared to other plants and beef.	[117]
Environmental sustainability of microalgae-based production systems: Roadmap and challenges towards the industrial implementation	♣	Microalgae cultivation showed wide-ranging energy use (~1–6000 kWh/kg) and chemical nutrient demand (~10–4000 g/kg), resulting in GHG emissions of 0.33–4256 kg $CO_{2,eq}$/kg, typically in the hundreds. Microalgal biofuels	Sixteen LCA studies, based on primary data from pilot-to-industrial scale plants, were analysed. Only a few regarded near-full-scale facilities (order of magnitude of the cultivation volume of 10 m^3 or higher). Electricity (especially for	[56]

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Table 2 (*continued*)

Title	$/♣	Main data	Highlights	Ref.
		had unfavourable NERs, and microalgal biodiesel production had GHG emissions of 70–250 kg $CO_{2,eq}$/kg. Astaxanthin production emitted 378–6119 kg $CO_{2,eq}$/kg.	systems with artificial illumination) and infrastructure represented the main environmental hotspots. Microalgal biofuels were not competitive with conventional (bio) fuels. High-value added biochemicals (e.g., pigments) were affected by low yields, which resulted in high environmental burdens. Improvement strategies were identified in multi-product biorefinery schemes and waste stream (wastewater and flue gas) valorisations. The variability in system features and LCA methodologies across studies led to major discrepancies in results, hindering comprehensive comparisons. Future research should focus on methodological harmonization, transparent reporting, and improved access to large-scale plant data.	
Carbon migration of microalgae from cultivation towards biofuel production by hydrothermal technology: A review	$, ♣	The GHG emissions of microalgal biofuels ranged from −75 to 534 g $CO_{2,eq}$/MJ. The NER (energy input/output) ranged from ~0.34–1.25, the MFSP was between 2.1 and 10.4 $/GGE, and the Energy Return on Investment (EROI) was < 1.	The lack of methodological standardisation made comparing LCA results difficult and led to uncertain mean trends. HTL showed a tendency to outperform other biomass conversion methods due to its higher energy efficiency. Wastewater treatment could result in carbon credits. The energy and economic indicators were not satisfactory, and further efforts in R&D activities are required to implement competitive systems.	[34]

cost data reported in Fig. 4, which reveals that the biomass production costs estimated by TEAs span a wide range, from 10^{-2} to 10^{2} $/kg, with the most frequent values falling between ~0.5 and 20 $/kg. For example, the biomass cost varied from ~0.6 $/kg to 25 $/kg in ref. [2], with most values clustering around 10 $/kg. In addition to high OpEx due to the electricity demand, labour cost and CapEx may also significantly impact the total biomass production costs [2,92,109]. Comparisons between ORP and PBR cultivation systems suggest that ORPs are generally more cost-effective, but this is not a fixed rule. Notably, systems based on attached biofilm cultivation seem to significantly reduce the energy consumption and biomass production costs compared to conventional suspended cultivations [108], indicating a promising area for further investigation.

As far as the environmental impacts are concerned, assuming an emission factor in the order of 1 kg $CO_{2,eq}$/kWh for fossil-based electricity [120], the abovementioned energy consumption of $O(10^2)$ kWh/kg would translate into high indirect emissions – 10^2 kg $CO_{2,eq}$/kg – rendering the cultivation process environmentally unsustainable. This estimate is broadly consistent with the LCA results reported in the literature, which largely focus on global warming potential, i.e., greenhouse gas (GHG) emissions, and typically fall around 100 kg $CO_{2,eq}$/kg, as shown in Fig. 4. However, the various data are scattered over a wide range from small negative values (indicating carbon credits) to thousands of kg $CO_{2,eq}$/kg biomass. In the specific case of pilot- or industrial-scale plants assessed using primary data, the warming potential ranges from 0.33 kg $CO_{2,eq}$/kg to 4256 kg $CO_{2,eq}$/kg [56]. This great variability can be ascribed to the different technical features of the assessed cultivation plants (microalgal strain, bioreactor type and scale, climatic conditions, process conditions, process inputs, and harvesting technique). Additionally, comparisons between ORPs and PBRs have yielded inconsistent findings: Smetana et al. [117] reported better performance for ORPs, Gurreri et al. [56] documented the opposite. Such discrepancies may also stem from different methodological choices and assumptions across LCA studies, underlining the need for methodological harmonisation (see Section 4.2). Finally, heterotrophic and mixotrophic cultivation systems have shown potential for higher biomass and valuable compound productivities compared to autotrophic processes, thereby resulting in appreciable economic and environmental benefits [86,98,112,117].

4.1.3. Biofuels

Beyond microalgal biomass, all the final microalgal bioproducts are characterised by a wide variability in economic and environmental performance, which makes their sustainability uncertain. Microalgal biofuels, in particular, have been the subject of extensive research efforts aimed at identifying sustainable alternatives to conventional fossil fuels. However, the present meta-review highlights that several challenges remain before microalgal biofuels can be considered sustainable. The various review studies generally converge on the conclusion that, under current conditions, microalgal biofuels are economically and environmentally uncompetitive. As shown in Fig. 5, most reported NER (defined as produced energy over consumed energy) values were below 1, indicating a negative energy balance. While some enhanced configurations have demonstrated an energy gain (i.e., NER > 1) [34,110], these case studies remain exceptions and still fall short of the competitiveness of oil products, which have a final-stage EROI of ~7 [121].

The estimated production cost of microalgal biofuels exhibits high dispersion, ranging from ~10 $/GJ to ~200 $/GJ (Fig. 5) and, in most cases, remains uncompetitive [2,88,99,110]. For context, the price of petroleum diesel in the USA in April 2025, excluding taxes as well as distribution and marketing costs, averaged around 15 $/GJ [122], whereas its price in Europe at the end of May 2025 was ~19 $/GJ [123]. These figures are lower than all the values of microalgal biodiesel costs reported by Liu et al. [88] and Hou et al. [95] (~23–172 $/GJ). Similar considerations can apply to other drop-in biofuels, as benchmark costs for petroleum-derived gasoline and jet fuel are comparable to diesel fuel

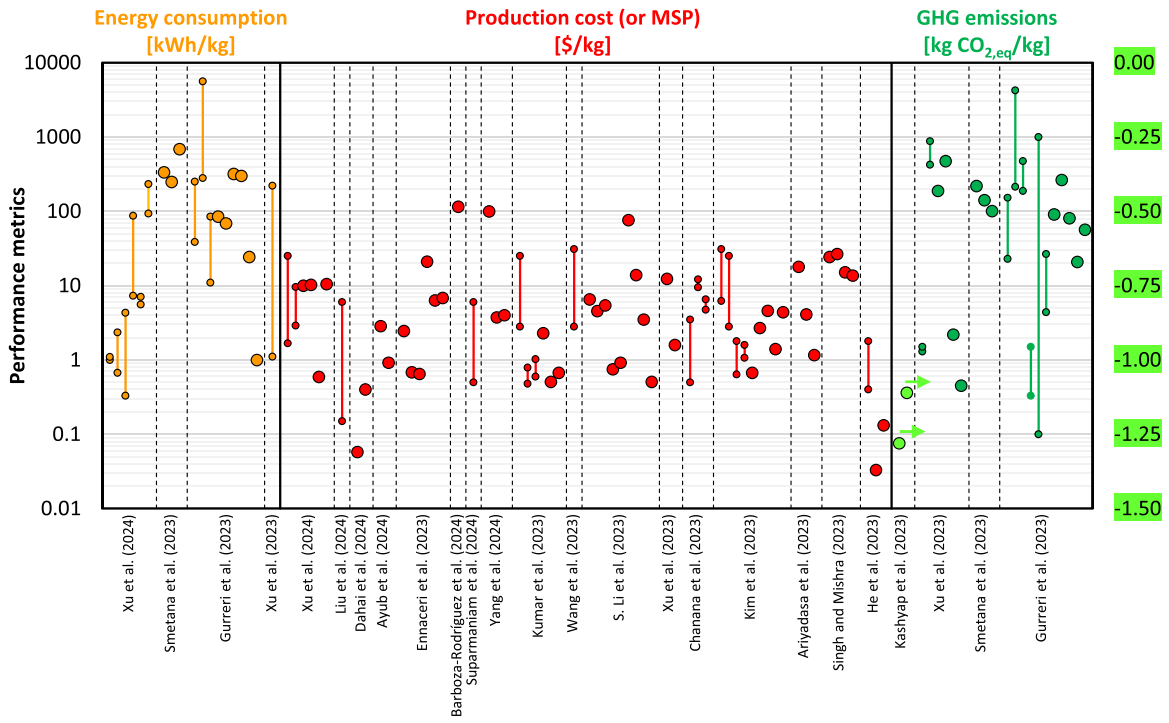

Fig. 4. Performance metrics for microalgal biomass production: energy consumption (orange, left), cost or Minimum Selling Price (red, center), and GHG emissions (green, right). The figure presents individual data points (large symbols) and ranges (small symbols) extracted from recent literature. The secondary y-axis on the right, displayed on a linear scale, represents negative GHG emission values (i.e., net carbon capture scenarios, light green). Data sources: Xu et al. [2], Smetana et al. [117], Gurreri et al. [56], Xu et al. [109], Liu et al. [88], Dahai et al. [1], Ayub et al. [87], Ennaceri et al. [108], Barboza-Rodríguez et al. [23], Suparmaniam et al. [92], Yang et al. [93], Kumar et al. [96], Wang et al. [97], Li et al. [107], Chanana et al. [111], Kim et al. [112], Ariyadasa et al. [113], Singh and Mishra [115], He et al. [34], and Kashyap et al. [101].

[122–124]. In contrast, the TEA estimations reported by Ayub et al. [87], Omer et al. [89], and Khan et al. [110] indicate that, with production costs in the overall range of 5–52 $/GJ, microalgae-derived biohydrogen can be cost-competitive with hydrogen produced through the dominant industrial method based on steam methane reforming technology without carbon capture (grey hydrogen, ~10 $/GJ in the USA [125] and ~30 $/GJ in Europe [126]). The competitiveness of microalgal biohydrogen improves further when compared to natural gas-based hydrogen technologies coupled with carbon capture and storage (blue hydrogen, ~14–21 $/GJ in the USA [125] and ~36 $/GJ in Europe [126]), and even more so relative to emerging technologies such as electrolysis and waste pyrolysis/gasification (~44–80 $/GJ [126]). However, these benchmark values are subject to considerable uncertainty, influenced by multiple factors such as CO_2 storage and transportation costs, electricity and gas prices, by-product revenues, and fluctuations in EU allowance prices [125,126].

Regarding the environmental dimension of sustainability, Fig. 5 highlights that microalgal biofuels are usually far from carbon neutrality and often more impactful than conventional fuels. Nevertheless, several LCAs have estimated that microalgal biofuels may be competitive or even yield carbon credits [34,97,111]. Overall, as with economic indicators, the environmental results show substantial variability across the analysed studies. For instance, Khan et al. [110] reported a GHG emissions range of ~1–7.5 kg $CO_{2,eq}$/kg biofuel, with the lowest and highest values for bioethanol and biohydrogen, respectively. Nevertheless, the ranking changes when the emissions are normalised per unit of energy content. On a per-GJ basis, bioethanol maintains the lowest emissions (25 kg $CO_{2,eq}$/GJ), whereas biocrude becomes the highest-emitting biofuel (160 kg $CO_{2,eq}$/GJ), and biohydrogen drops to a moderate level (~60 kg $CO_{2,eq}$/GJ). The case study on biodiesel reported by Khan et al. [110] shows the second-lowest value of GHG emissions (~54 kg $CO_{2,eq}$/GJ). Interestingly, the environmental performance of microalgal biohydrogen appears particularly promising, as its GHG emissions are lower than those from steam methane reforming [87] (benchmarks are between ~75 and 108 kg$CO_{2,eq}$/GJ [125,126]). These findings suggest that, under optimized conditions, microalgal biohydrogen could offer a viable low-carbon alternative in the hydrogen economy. However, microalgal biohydrogen may still exhibit higher environmental impacts compared to blue hydrogen and other emerging production pathways [125,126]. Furthermore, only one case study has been documented on microalgal biohydrogen across the analysed reviews [87,110]; hence, multiple evidence should be provided from other studies to confirm or deny these results. In the work by He et al. [34], the whole range of GHG emissions of microalgal biofuels was −75 to 534 kg $CO_{2,eq}$/GJ. Microalgal biodiesel production demands intensive material and energy inputs [94], which may lead to higher GHG emissions compared to petroleum diesel (~15 kg $CO2_{,eq}$/GJ, rising to ~90 kg $CO2_{,eq}$/GJ when vehicle combustion is included [127,128]), although controversial results have been found. For example, Aslanbay Guler et al. [77] reported two markedly different values of GHG emissions for microalgal biodiesel, namely 330 and ~16 kg $CO_{2,eq}$/GJ. The higher figure refers to a cradle-to-gate analysis for a case study involving supercritical CO_2 extraction, while the lower value comes from a well-to-wheels assessment (i.e., including combustion emissions) for a case study based on subcritical water extraction. Based on system boundaries, higher GHG emissions would be expected when combustion is included in the analysis. However, the opposite result is observed here, suggesting that other key factors can significantly influence the overall environmental performance. It is important to note that the system boundaries of the case studies documented in the analysed reviews were often unspecified, making comparisons potentially misleading. In contrast, only a limited number of review studies indicated explicitly the system boundary (for instance, refs. [56,77,129]), underscoring the need for more transparent methodological reporting. Other examples of microalgal biodiesel GHG emissions include ~29, 33, and −2 kg $CO_{2,eq}$/GJ from HTL, 111.2 kg $CO_{2,eq}$/GJ from

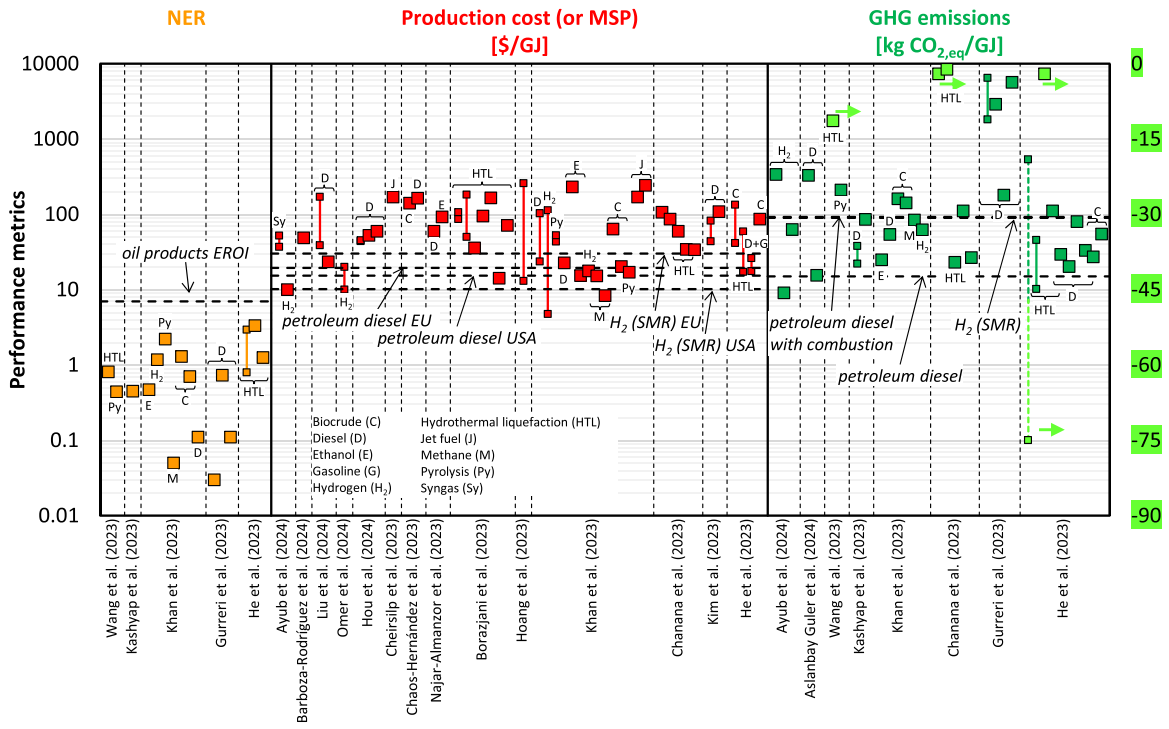

Fig. 5. Performance metrics for microalgal biofuels: NER (orange, left), cost or Minimum Selling Price (red, center) and GHG emissions (green, right). The figure presents individual data points (large symbols) and ranges (small symbols) extracted from recent literature. When the biofuel was not specified in the references, biodiesel was assumed for the conversion of mass or volume into energy content. The secondary y-axis on the right, displayed on a linear scale, represents negative GHG emission values (i.e., net carbon capture scenarios, light green). Where available, the specific final bioproduct is preferentially indicated; otherwise, the main conversion process (e.g., HTL route, with or without subsequent refinement) is shown. If neither was provided in the reference source, the corresponding label in the chart is left blank. Data sources: Wang et al. [97], Kashyap et al. [101], Khan et al. [110], Gurreri et al. [56], He et al. [34], Ayub et al. [87], Barboza-Rodríguez et al. [23], Liu et al. [88], Omer et al. [89], Hou et al. [95], Cheirsilp et al. [98], Chaos-Hernández et al. [99], Najar-Almanzor et al. [100], Borazjani et al. [104], Hoang et al. [105], Chanana et al. [111], Kim et al. [112], and Aslanbay Guler et al. [77]. Relevant benchmarks are reported for comparison purposes: oil products EROI [121], cost of petroleum diesel in the USA [122] and EU [123], cost of hydrogen (steam methane reforming) in the USA [125] and EU [126], well-to-gate and well-to-wheel GHG emissions of petroleum diesel [127,128], and GHG emissions of hydrogen production (steam methane reforming) [125,126].

fermentation-HTL, 20 kg $CO_{2,eq}$/GJ from lipid extraction, and 80 kg $CO_{2,eq}$/GJ from anaerobic digestion [34]. HTL generally outperforms biochemical conversion techniques for biocrude production [34], a finding confirmed by multiple studies. Among thermochemical conversion processes, Wang et al. [97] reported GHG emissions of –11.4 kg $CO_{2,eq}$/GJ for HTL vs. 210 kg $CO_{2,eq}$/GJ for pyrolysis, though both pathways exhibited unfavourable NER values. The HTL way differs notably from traditional biodiesel production methods, offering the benefit of avoiding the use of toxic solvents typically required for lipid extraction. Similarly, supercritical extraction processes for microalgae-to-biodiesel conversion have been suggested as environmentally favourable options [88]. Despite these advantages, GHG emissions associated with the HTL route remain variable, as data points are quite dispersed. Although no specific case studies were identified for microalgal gasoline and jet biofuels, they may be expected to follow an HTL-and-upgrade route. Hence, their comparative performance remains uncertain when measured against the petroleum-based benchmarks of ~15 kg $CO_{2,eq}$/GJ for well-to-refinery-gate and 90 kg $CO_{2,eq}$/GJ for well-to-wake [128,130], especially considering the absence of clear system boundaries. Finally, focusing on assessments based – at least for the cultivation stage – on primary data from pilot installations, GHG emissions of microalgal biodiesel ranged from 180 to almost 6500 kg $CO_{2,eq}$/GJ [56]. These robust evaluations strengthen the evidence for (i) the high variability and sensitivity of results to specific case studies, and (ii) the environmental uncompetitiveness of microalgal biodiesel.

4.1.4. *Biocompounds*

Only a limited dataset could be extracted from the analysed review studies concerning the various phytochemicals derived from microalgae (Fig. 6). Lipids (precursors for biofuels but also various high-value nutraceuticals, such as PUFAs, and chemical intermediates to produce biopolymers) exhibited extremely variable production costs. Data reported by Liu et al. [88] (regarding general lipids or triglycerides) were notably lower than those presented by Chaos-Hernández et al. [99] (referring to lipids and fatty acids). In the latter review study, five values of around 1000 $/kg were distinguished from a single value of ~27000 $/kg, which was for a case study with a green solvent-based extraction of fatty acids. Although benchmarks on vegetable oils production cost vary significantly based on multiple factors [131], several commercial products are priced around 1.1 $/kg [132], rendering microalgal lipids uncompetitive. Even worse, the estimated cost of fish oil DHA of ~11 $/kg [133] is orders of magnitude lower than the production cost of microalgae-derived fatty acids [99]. In terms of environmental performance, the GHG emissions of microalgal lipids (DHA-rich *Schizochytrium* oil and fatty acids) were in the range of ~9–20 kg $CO_{2,eq}$/kg [56,77]. These values are considerably higher than those typically associated with vegetable oils, animal fats, and reused feedstocks [127], as well as fish oil [134], further challenging the sustainability of microalgal lipid production under current technological and economic conditions.

Microalgae-derived proteins have been proposed as alternative foods and supplements, but their performance metrics show considerable variability (Fig. 6). The estimated production costs are from ~1.5 $/kg to 20 $/kg [93,103]. Considering the wide range of the production cost for conventional (animal and vegetal) and unconventional (single-cell, e.g., fungi-derived) proteins [135], and the even broader range of protein sources market price [136], microalgal proteins demonstrate promising potential for economic competitiveness, albeit based on a limited dataset. The GHG emissions of microalgal protein production are

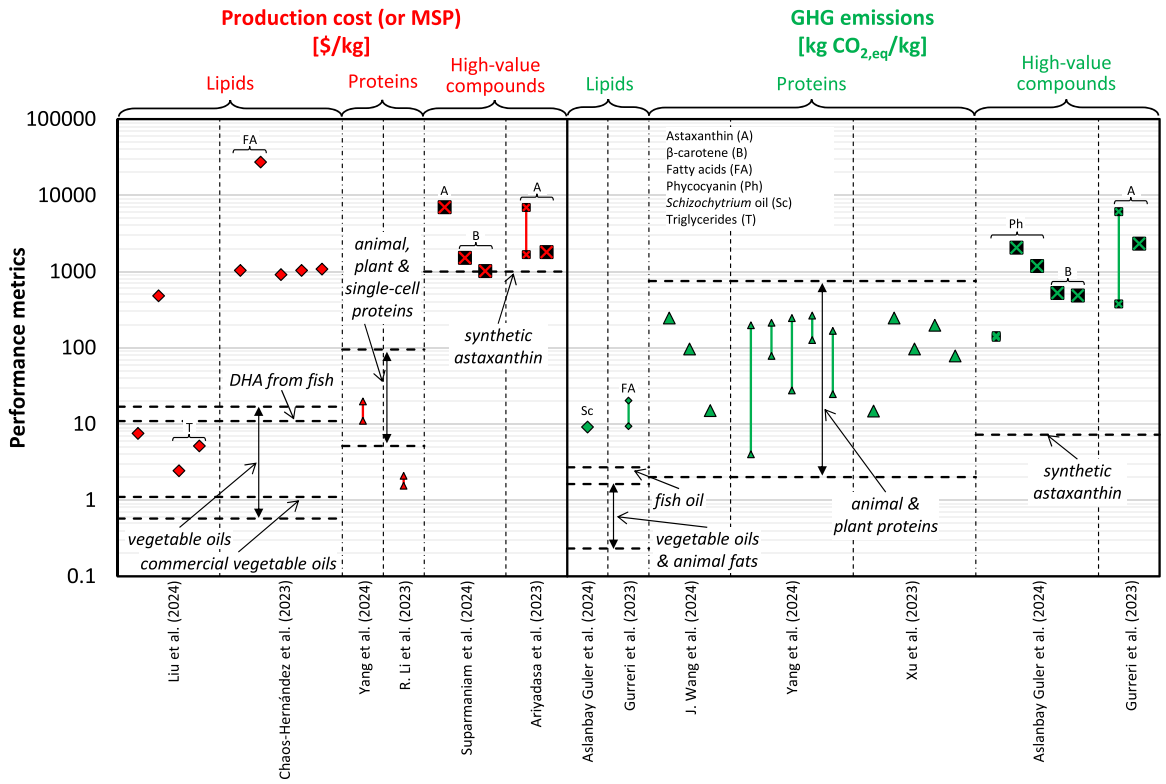

Fig. 6. Performance metrics for microalgal bio-compounds: cost or Minimum Selling Price (red, left) and GHG emissions (green, right). The figure presents individual data points (large symbols) and ranges (small symbols) extracted from recent literature. Where available, the specific final bioproduct is indicated. Data sources: Liu et al. [88], Chaos-Hernández et al. [99], Yang et al. [93], Li et al. [103], Suparmaniam et al. [92], Ariyadasa et al. [113], Aslanbay Guler et al. [77], Gurreri et al. [56], Wang et al. [86], Yang et al. [93], and Xu et al. [109]. Relevant benchmarks are reported for comparison purposes: vegetable oils cost [131] and commercial price [132], fish-derived DHA cost [133], proteins cost [135], synthetic astaxanthin cost [137], oils and fats GHG emissions [127], fish oil GHG emissions [134], proteins GHG emissions [93,117,136], and synthetic astaxanthin GHG emissions [138].

from 4 to 264 kg $CO_{2,eq}$/kg, with most values skewed toward the higher end [86,93,109]. Moreover, high energy consumption values were reported [86]. However, the sustainability of microalgal protein production is highly dependent on the cultivation system. For example, heterotrophic cultivation can cut the energy demand and GHG emissions compared to ORPs or tubular PBRs [86]. Benchmarks on GHG emissions of conventional protein sources are similarly dispersed. According to ref. [136], cradle to retail gate emissions for animal- and plant-based proteins are scattered from a few units to several hundred kg $CO_{2,eq}$/kg protein (mean of ~43 kg $CO_{2,eq}$/kg and median of ~30 kg $CO_{2,eq}$/kg). Other sources reported even wider ranges for animal protein (~20–750 kg $CO_{2,eq}$/kg) [93], and myco- and plant-based protein (~2–40 kg $CO_{2,eq}$/kg) [117]. Overall, when environmental performance is solely evaluated as GHG emissions, microalgal proteins appear to be environmentally competitive with meat-based proteins.

A distinctive feature of microalgae-derived bioactive compounds, such as carotenoids and pigments, is their exceptionally high market value, which makes them very attractive for industrial applications. For example, various antioxidants are valued at ~300–800 $/kg [2], while astaxanthin may reach up to 5000 $/kg [113]. Despite this economic appeal, their commercial viability is hindered by low productivity, techno-economic immaturity [92,113], and poor environmental performance [56,77]. As shown in Fig. 6, production costs for these compounds are in the range of ~1000–7000 $/kg, and their GHG emissions are in the range of ~140–6000 kg $CO_{2,eq}$/kg. For example, the production of microalgae-derived astaxanthin was found to be too expensive and uncompetitive when compared to its chemically synthesized counterpart [92,113], which has a production cost of ~1000 $/kg [137]. Moreover, the environmental burden of microalgal astaxanthin production is significantly higher, with GHG emissions far exceeding the ~7 kg $CO_{2,eq}$/kg associated with synthetic production [138]. However, the choice of extraction method can markedly influence sustainability outcomes. Green extraction techniques, such as those employing supercritical fluids, pulsed electric fields, or ultrasound-assisted processes, can help mitigate environmental impacts of microalgal bioactive compounds [77,90]. For instance, Aslanbay Guler et al. [77] reported that the pulsed electric field method for phycocyanin extraction was substantially less impactful than the ultrasound-based method (~140 kg $CO_{2,eq}$/kg vs. 1180 or 2060 kg $CO_{2,eq}$/kg).

4.1.5. *Main strategies for performance improvement*

Despite the generally unfavourable sustainability outcomes identified for microalgal biomass and its derived products, several strategies hold considerable promise for improving the economic and environmental performance of microalgae-based systems. Based on the examination of Table 2 and as illustrated in Fig. 7, three key enhancement strategies emerge: i) the recovery and valorisation of wastewater and other waste streams for microalgae cultivation, ii) the adoption of a biorefinery approach, and iii) the deployment of low-carbon energy technologies (e.g., renewables) to power the production process. Fig. 8 collects relevant data on production costs and GHG emissions from scenarios that incorporate one or more of these strategies. Where available, corresponding data from base cases (i.e., those without the improvement measures) are also included to offer a more comprehensive framework. A summary of each improvement scenario is provided in Table 3.

Overall, Fig. 8 shows encouraging results for microalgal bioproducts under scenarios with potential improvement strategies. Compared with the relevant benchmarks, the most promising estimates suggest that microalgae-derived biofuels – e.g., diesel and jet biofuels – as well as

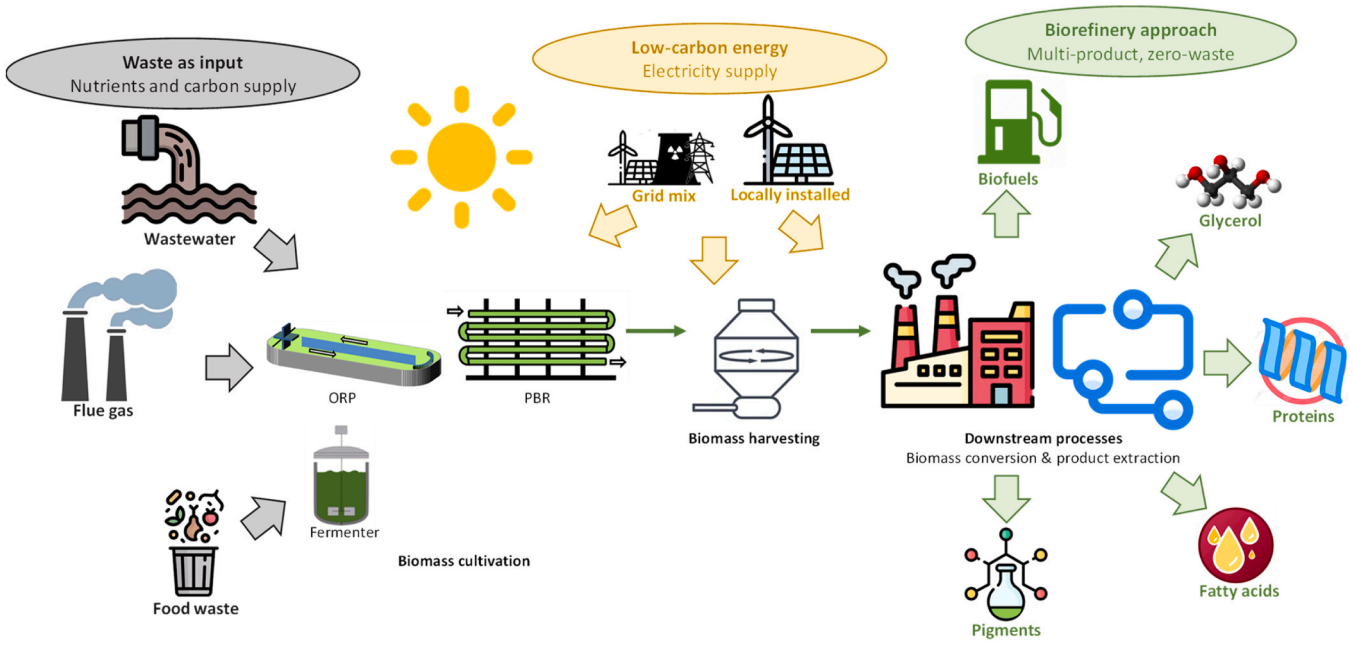

Fig. 7. Main strategies with some examples to enhance the sustainability of the microalgal industry: valorisation of waste as input for nutrient and carbon supply, implementation of a biorefinery approach with multi-product and zero-waste production, and deployment of low-carbon energy technologies for the electricity supply. The schematic illustration represents a generic industrial plant, comprising biomass cultivation and harvesting, followed by downstream processing for biomass conversion and product extraction.
The ORP and PBR images are reproduced from [139] with permission from Elsevier.

lipids and proteins, can achieve economic and environmental competitiveness. Notably, some case studies report lower production costs or GHG emissions than traditional products, and in certain cases, even net carbon credits are observed. The effectiveness of each improvement strategy is examined in the following.

As illustrated in Fig. 7, waste streams can serve as input materials for nutrient and carbon supply in photoautotrophic or heterotrophic microalgae cultivation (upstream section). Fig. 8 highlights that most data extracted from the analysed review studies focus on this improvement strategy (grey-shaded areas), confirming that circular bioeconomy approaches have received the most attention in TEA and LCA studies. Cultivating microalgae in wastewater offers a valuable opportunity to reduce the costs and environmental impacts associated with chemical fertiliser use, which represents one of the most important criticalities of microalgal production systems. Freshwater saving is an obvious side-effect, and the co-functionality of wastewater treatment adds to the economic and environmental value of this approach. In this regard, high-rate algal ponds can be more energy-efficient and cost-effective than conventional activated sludge systems [114]. Further opportunities derive from using waste streams as carbon sources. For example, CO_2 captured from flue gas produces carbon credits that reduce the overall GHG emissions. When combined with wastewater treatment, this strategy boosts the economic and environmental co-benefits. However, Chanana et al. [111] highlighted the need for further TEA and LCA studies to validate the real applicability of such systems. Food waste has also been explored as a substrate in heterotrophic cultivations. According to Fig. 8, microalgal biomass production using waste streams was estimated to cost ~0.2–11 $/kg (case studies 1–8). While flue gas alone showed limited economic improvement (case studies 1–4) compared to the base cases from Fig. 4, the lowest reported biomass cost was exceptionally achieved under this strategy (case study 7). Using wastewater – alone or in combination with flue gas (case studies 5, 6, and 8) – resulted in biomass costs within the lower range of base values from Fig. 4, confirming its cost-effectiveness. Of the three LCA case studies (26–28), two reported near-zero or negative GHG emissions, indicating environmental advantages. For microalgal biofuels, using waste-based inputs resulted in (i) all estimated production costs below 55 $/GJ (case studies 9–18) and (ii) most data points on GHG emissions below 90 kg $CO_{2,eq}$/GJ (case studies 31–44), including several scenarios with net carbon credits. The most promising cost estimates for biodiesel are around 20 $/GJ (case studies 11 and 12) for both photoautotrophic and heterotrophic cultivation regimes. On average, the "waste as input" strategy outperforms the base values reported in Fig. 5, suggesting significant enhancement potential. Regarding microalgal lipids, data on production costs (case studies 21–24) and GHG emissions (case study 46) show that wastewater use can substantially reduce costs (case study 24) compared to the most optimistic base values in Fig. 6, and that heterotrophic cultivation with food waste can lower the carbon footprint (case study 46). In contrast, flue gas use showed no significant economic benefit (case studies 21–23). Additional evidence from the analysed review studies supports the benefits of using waste streams as input. They include a 50 % reduction in the cultivation costs when food wastewater is used, and a reduction in the cultivation cost and emissions of ~10 % and 50 %, respectively, through internal wastewater recycling (closed-loop cultivation) [86]. Moreover, waste CO_2 reduced GHG emissions by ~20 % compared to pure CO_2 [77], waste sources for nutrients and flue gas reduced the microalgal lipid production costs by 36–95 % [97], wastewater could reduce environmental burdens by as much as five-fold [114], and biodiesel from microalgae cultured in domestic wastewater had an ROI of 41 % and a payback period of 2 years [1].

The second key strategy for improving the sustainability of microalgae-based systems involves the biorefinery approach, which targets the downstream phase of production and entails multiproduct industrial schemes designed to valorise by-products and minimise waste (Fig. 7). This strategy is recommended as the primary way of extracting the maximum economic value from microalgae and simultaneously mitigating their environmental burdens, thus boosting the profitability [92,109] and the environmental profile [56] of microalgal industries. Fig. 8 presents data from three case studies aligned with the biorefinery concept (green-shaded areas). The valorisation of residual biomass and by-products can help enhance the economic feasibility of microalgal

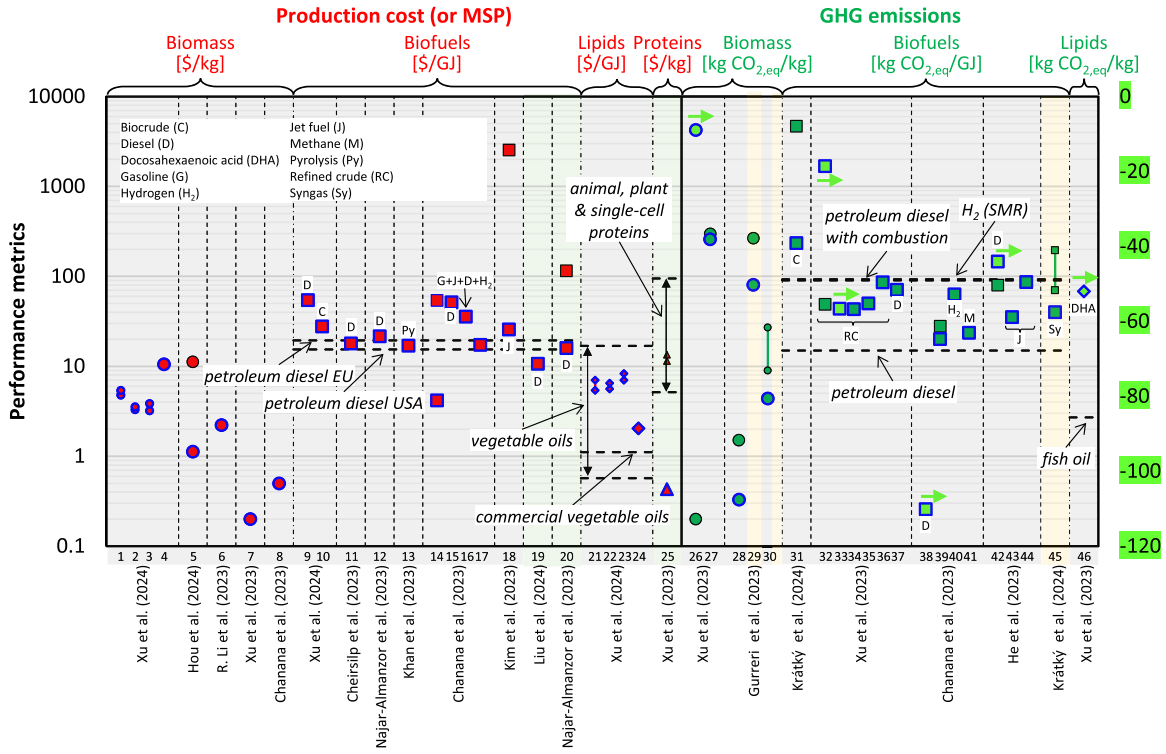

Fig. 8. Performance metrics for microalgal bioproducts in scenarios with potential sustainability improvements (symbols with a blue border): cost or Minimum selling Price (red, left) and GHG emissions (green, right). Where available, data from base cases (i.e., without the improvement strategy) are reported (symbols with a black border). The figure presents individual data points (large symbols) and ranges (small symbols) extracted from recent literature. When the biofuel was not specified in the references, biodiesel was assumed for the conversion of mass or volume into energy content. The secondary y-axis on the right, displayed on a linear scale, represents negative GHG emission values (i.e., net carbon capture scenarios, light green). Where available, the specific final bioproduct is indicated. Numbers are used to identify each scenario (see Table 3). The enhancement strategies are highlighted as coloured areas: waste as input for nutrients and carbon supply (grey areas), the multi-product biorefinery concept (green areas), and low-carbon energy technologies for electricity supply (yellow areas). Case study 30 couples waste as input and renewable energy strategies (grey and yellow areas). Duplicated data (four case studies) from different reviews were eliminated. Data sources: Xu et al. [2], Hou et al. [95], Li et al. [103], Xu et al. [109], Chanana et al. [111], Cheirsilp et al. [98], Najar-Almanzor et al. [100], Khan et al. [110], Kim et al. [112], Liu et al. [88], Gurreri et al. [56], Krátký et al. [91], and He et al. [34]. Relevant benchmarks are reported for comparison purposes: cost of petroleum diesel in the USA [122] and EU [123], vegetable oils cost [131] and commercial price [132], proteins cost [135], well-to-gate and well-to-wheel GHG emissions of petroleum diesel [127, 128], GHG emissions of hydrogen production (steam methane reforming) [125,126], and fish oil GHG emissions [134].

biofuels. For example, the biodiesel production cost was reduced to nearly 10 $/GJ (case study 19). Co-producing biofuels and high-added value products represents another promising route. For example, astaxanthin co-production led to a biodiesel cost of ~16 $/GJ (case study 20). Another interesting result was the cost of protein food of 0.43 $/kg from lipid-extracted microalgal residues in biodiesel co-production (case study 25). One TEA also reported a substantial improvement in profitability: a payback time of 2.62 y (and an ROI of ~38 %) in a co-production scenario involving proteins, fatty acids, and pigments, compared to a 6.38 y payback time for a protein-only base case [92]. On the environmental side, several studies have documented the benefits of biorefinery concepts in mitigating potential environmental impacts. Examples include the valorisation of protein-rich biomass and glycerol co-products from biodiesel production, and the exploitation of residual biomass from astaxanthin extraction, via either anaerobic digestion or feed production [56]. However, the commercial potential of microalgal biorefineries remains a matter of debate. While Wang et al. [97] claimed that the commercial returns of microalgal biorefineries were not satisfactory, Chanana et al. [111] identified eight international companies actively producing biorefinery-based products from microalgae, signalling some commercial traction. Overall, while the biorefinery concept shows significant promise, further research is needed to explore its numerous potential configurations across a broad spectrum of alternative solutions and to identify the most efficient and scalable pathways.

Given the typically high energy consumption in upstream and downstream processes, the third strategy for enhancing the sustainability of microalgal production systems consists of using low-carbon energy technologies. This approach can significantly mitigate the high carbon footprint linked to fossil-based systems, and may also contribute to cost reductions. Preferably, microalgal facilities should be located in regions served by electricity grid mixes with a high share of low-carbon energy technologies (i.e., renewables or nuclear power), or be coupled with on-site renewable installations such as photovoltaic panels or wind turbines (Fig. 7). Notably, the most optimistic assessments report that renewable energy integration reduced the global warming potential by as much as 99 % [3]. Fig. 8 includes a few data points on environmental improvements introduced by the deployment of low-carbon energy (yellow-shaded areas). In case study 29, the GHG emissions of microalgal biomass production dropped from ~265 kg $CO_{2,eq}$/kg to ~81 kg $CO_{2,eq}$/kg when switching from the German grid mix (largely fossil-based) to the French grid mix (predominantly nuclear). Moreover, a 36 % average reduction in environmental impacts was observed when switching from the Italian to the Norwegian grid mix (98 % hydropower) [56]. In case study 30, a photovoltaic system combined with wastewater and flue gas inputs reduced biomass GHG emissions from ~10–30 kg $CO_{2,eq}$/kg to ~4 kg $CO_{2,eq}$/kg, with significant benefits over the Spanish grid mix achieved through renewable energy. Furthermore, a 75 % substitution of the European electricity mix with photovoltaic energy reduced the estimated GHG emissions by more than 50 % [109]. From an economic perspective, innovations such as photovoltaic-powered PBRs with LED lighting and Arduino microcontrollers reduced cultivation costs of nearly 50 % [115]. However,

Table 3
Summary of the specific improvement strategies adopted in the scenarios represented in Fig. 8, detailing the interventions contributing to enhanced economic or environmental performance.

Case study	Performance metric	Bioproduct	Strategy	Case study description	Ref.
1	Production cost	Biomass	Waste as input	Cultivation with flue gas	[2]
2	"	"	"	Cultivation with flue gas	"
3	"	"	"	Cultivation with flue gas	"
4	"	"	"	Cultivation with flue gas	"
5	"	"	"	Cultivation in municipal wastewater and flue gases from a power plant	[95]
6	"	"	"	Cultivation in liquid digestate	[103]
7	"	"	"	Cultivation with industrial waste CO_2	[109]
8	"	"	"	Cultivation in wastewater	[111]
9	"	Biofuels	"	Cultivation with flue gas	[2]
10	"	"	"	Cultivation in wastewater	"
11	"	"	"	Heterotrophic cultivation with VFA from food waste	[98]
12	"	"	"	Cultivation in wastewater	[100]
13	"	"	"	Cultivation in centrate wastewater	[110]
14	"	"	"	Cultivation with pure sources of gaseous CO_2 from waste	[111]
15	"	"	"	Cultivation in wastewater and with flue gas	"
16	"	"	"	Cultivation in wastewater	"
17	"	"	"	Cultivation in wastewater	"
18	"	"	"	Cultivation with food byproducts	[112]
19	"	"	Biorefinery	Economic value of residual biomass and glycerol by-products	[88]
20	"	"	"	Astaxanthin co-production	[100]
21	"	Lipids	Waste as input	Cultivation with flue gas	[2]
22	"	"	"	Cultivation with flue gas	"
23	"	"	"	Cultivation with flue gas	"
24	"	"	"	Cultivation in wastewater and with flue gas	"
25	"	Proteins	Biorefinery	Biodiesel co-production	[109]
26	GHG emissions	Biomass	Waste as input	Cultivation in wastewater and with gasoline combustion gas	[109]
27	"	"	"	Cultivation with waste CO_2	"
28	"	"	"	Cultivation in wastewater and with flue gas	[56]
29	"	"	Low-carbon energy	French grid mix (high share of nuclear power)	"
30	"	"	Waste as input + Low-carbon energy	Cultivation in wastewater and with flue gas + photovoltaic panels	"
31	"	Biofuels	Waste as input	Cultivation in wastewater	[91]
32	"	"	"	Cultivation with CO_2 from a biomass combustion plant	[109]
33	"	"	"	Cultivation with CO_2 from a biomass gasification plant	"
34	"	"	"	Cultivation with CO_2 from a coal-based power plant	"
35	"	"	"	Cultivation with CO_2 from a natural gas power plant	"
36	"	"	"	Cultivation with CO_2 from an NGCC plant	"
37	"	"	"	Cultivation with CO_2 flue gas	"
38	"	"	"	Cultivation in wastewater and with flue gas	[111]
39	"	"	"	Cultivation with pure sources of gaseous CO_2 from waste	"
40	"	"	"	Cultivation in wastewater and microalgae gasification (to produce H_2) with steam generated by burning waste gases from pressure swing adsorption	"
41	"	"	"	Cultivation in wastewater and microalgae gasification (to produce CH_4) with steam generated by burning waste gases from pressure swing adsorption	"
42	"	"	"	Cultivation in wastewater	[34]
43	"	"	"	Cultivation in wastewater	"
44	"	"	"	Cultivation in wastewater	"
45	"	"	Low-carbon energy	Solar system for algal slurry drying	[91]
46	"	Lipids	Waste as input	Heterotrophic cultivation with food waste	[109]

LCA studies highlighted the detrimental effects of photovoltaic systems in some environmental impact categories (human toxicity and metal depletion), despite the significant reduction (68 %) in carbon footprint [56]. This drawback may be mitigated by harnessing direct solar energy. For example, in case study 45, solar drying of algal slurry for syngas production reduced GHG emissions from 70 to 195 kg $CO_{2,eq}$/GJ (for conventional drying) to less than 40 kg $CO_{2,eq}$/GJ. Light source selection also plays a crucial role in the environmental and economic performance of photoautotrophic cultivation systems. In a comparative LCA (which included case study 29) of closed PBRs, an outdoor cultivation pilot plant using sunlight resulted in the lowest value of GHG emissions (~21 kg $CO_{2,eq}$/kg biomass), outperforming LED-illuminated systems. Despite these insights, the comparative assessment of natural vs. artificial light for microalgal photosynthesis remains underexplored in the reviewed literature, highlighting a key area for further investigation.

Finally, the simultaneous implementation of all three suggested strategies (waste as input, biorefinery approach, and low-carbon energy) holds significant potential to maximise the economic and environmental performance of microalgal production systems. This holistic approach could result in a tremendous boost in the overall sustainability and commercial viability of the microalgal industry. However, several limitations must be acknowledged. For example, due to sanitary regulatory constraints, microalgae cultivation in wastewater is incompatible with the production of nutraceutical and pharmaceutical bioproducts. This restricts the applicability of strategies depending on the intended bioproduct end-uses. Therefore, context-specific assessments and careful trade-off evaluations are necessary to optimise process configurations based on target markets and sustainability goals.

4.2. *Challenges and the way forward in sustainability assessments*

Analysing Table 2 prompts a broader discussion on the underlying data quality, methodologies, and tools employed in sustainability assessments. A key concern is the scale of the experimental systems that generate input data for TEAs and LCAs. Indeed, reliable and realistic estimations of economic and environmental indicators for industrial

applications demand primary technical data from large-scale plants (e.g., pre-commercial facilities) [110] that operate under real-world conditions. To date, however, such data have been poorly documented, and most TEA and LCA studies rely on inputs derived from laboratory or pilot-scale experiments [56,77,107], thereby introducing severe inaccuracies and uncertainties into extrapolations for industrial-scale projections.

Beyond technical differences and scale-up assumptions, methodological heterogeneities and modelling choices further exacerbate uncertainty and variability in TEA and LCA outcomes, making direct comparisons challenging [34,56,107]. To address this, a common harmonization framework is needed, beginning with consistent functional-unit definitions (e.g., 1 kg of dry biomass or 1 GJ of biofuel) but extending to standardized protocols for scaling laboratory data, selecting the model boundaries, assessing environmental impacts, and selecting economic indicators. Cruce et al. [140], starting from sixty TEA and LCA, demonstrated comparability across twenty-eight assessments on algal biofuels through retrospective harmonization. Although Bradley et al. [141] established a prospective LCA protocol for three demonstration projects (joint goal and scope definition, FU = "1 MJ Lower Heating Value of algal biofuel combusted in a car engine," unified life cycle inventory indicators and impact categories, and system-expansion for multifunctionality), further effort is required to develop a fully unified methodology that enables straightforward, transparent comparisons without reliance on complex post hoc meta-models. Moreover, uncertainty, sensitivity and scenario analyses should be intensified and harmonised in a shared approach to enhance the robustness and comparability of model outcomes.

Interestingly, none of the reviewed articles explicitly address life cycle costing (LCC), despite its relevance alongside TEA. While LCC is less frequently applied, it remains a crucial method for evaluating the cradle-to-grave economic performance of production systems. When present, reviews should clearly differentiate between TEA and LCC approaches. Beyond internal costs caused by actors in the life cycle, LCC can incorporate relevant costs associated with environmental and even social externalities [142,143]. About the social dimension, social LCA (SLCA) could quantify impacts such as employment and job creation, community engagement, health and safety, resource access, and social equity in microalgal industries [129], yet no SLCA studies were identified. To fully capture the holistic sustainability of microalgal bioproducts, future research must strengthen economic and social life cycle thinking approaches and explore combined frameworks. For example, coupling LCA with LCC can identify both environmentally and economically optimal options, or integrating TEA and LCA can balance technical, financial, and environmental considerations and determine the optimal scale of production [10]. Ultimately, unifying LCA, LCC, and SLCA within a comprehensive life cycle sustainability assessment (LCSA) framework would offer the multidimensional insights necessary for fully informed decision-making [10,143].

Moreover, methodologies for economic and environmental assessment could be integrated into superstructure-based multi-objective optimisation frameworks to identify best trade-offs between minimum environmental impact and maximum economic profitability in the process design of microalgal biorefineries [129]. For example, Kopton et al. (2023) [144] developed a superstructure model that couples cradle-to-gate LCA with economic objectives, generating Pareto-optimal configurations to design sustainable microalgae processing pathways.

Process systems engineering (PSE) underpins this approach by uniting process design, modelling, and control into a coherent multi-objective optimization workflow (economic and environmental targets) to drive decision-making [82,145]. Advanced plant-wide simulation models, both static and dynamic, can capture multi-scale phenomena in photobioreactors – linking cell-scale kinetics to reactor-scale transport [146] – and support conceptual design and scenario analysis, while learning-curve projections can translate first-of-a-kind techno-economic estimates into nth-of-a-kind performance scenarios, enabling robust scalability assessments and far more accurate economic insights than traditional, simplistic cost evaluations. However, the lack of robust data from large-scale operations and the numerical complexity of large superstructures remain key challenges for model validation and solution tractability [82,145]. Complementary exergy-based methods, namely exergoeconomic and exergoenvironmental analyses, further enrich decision support by quantifying resource inefficiencies alongside economic and environmental impacts [147].

4.3. SWOT analysis and real-world applicability

Scaling up microalgae-based production systems must navigate a complex landscape of technical, economic, environmental, social, and regulatory challenges before true industrial deployment. Whether projects on microalgal systems fail or succeed depends on multiple interrelated factors. Fig. 9 presents these as a SWOT framework, mapping internal Strengths and Weaknesses alongside external Opportunities and Threats to give a concise overview of the variables that govern process sustainability and real-world applicability.

This pathway can be founded on the intrinsic advantages offered by microalgae. Microalgae represent a renewable raw material with a rich biodiversity (hundreds of thousands of species) and that contains lipids, carbohydrates, proteins, and high-added value components, which can be exploited to produce a wide range of final bioproducts, even simultaneously. Additional strengths include the effectiveness of integrating microalgae cultivation with the treatment/valorisation of waste streams, such as wastewater, CO_2-rich flue gas (autotrophic conditions), or organic matter from food waste and by-products (heterotrophic conditions).

Several weaknesses that can impair the performance of microalgal technologies and affect their economic competitiveness and environmental sustainability have emerged. Microalgae-based production systems are characterised by low biomass and bioproduct productivity, which is further compounded by negative energy balances and high levels of material consumption, production costs, and associated environmental burdens. In this regard, the carbon emission balance is generally unfavourable and does not meet the carbon neutrality targets. Moreover, the potential advantages of integrating wastewater treatment are confined to specific applications, and several bioproducts (e.g., pharmaceuticals and nutraceuticals) are excluded for sanitary reasons. Finally, many microalgal processes remain at a low Technology Readiness Level (TRL), indicating a limited maturity of many microalgal technologies and process layouts.

Sustainable microalgal companies can leverage several opportunities to empower their strengths and mitigate their weaknesses. Foremost, the enhancement strategies discussed in Section 4.1.4 should be fully exploited. On one hand, industrial symbiosis and circular bioeconomy models can be the paramount drivers of eco-efficiency and eco-effectiveness measures. Indeed, using by-products and waste streams from production lines or the end-of-life stages of other products can reduce resource consumption and close material cycles, thereby creating various opportunities to derive economic and environmental benefits. On the other hand, the multi-product biorefinery approach can maximise the value extracted from microalgal biomass. The deployment of low-carbon energy technologies to power microalgal industries and the direct use of sunlight, e.g., in photoautotrophic cultivations, can be considered another external factor that can lead towards sustainable solutions. Additionally, the high market value of some microalgal bioproducts (e.g., pigments and PUFAs) can serve as a critical economic enabler. Technological innovation presents another major opportunity. Among others, advances in genetic engineering [3] and artificial intelligence [148,149] can be mentioned as prominent examples. Another key source of opportunities is the implementation of pilot and demonstration projects, which are essential for boosting process maturity and scaling microalgae applications. In this regard, suitable R&D funding,

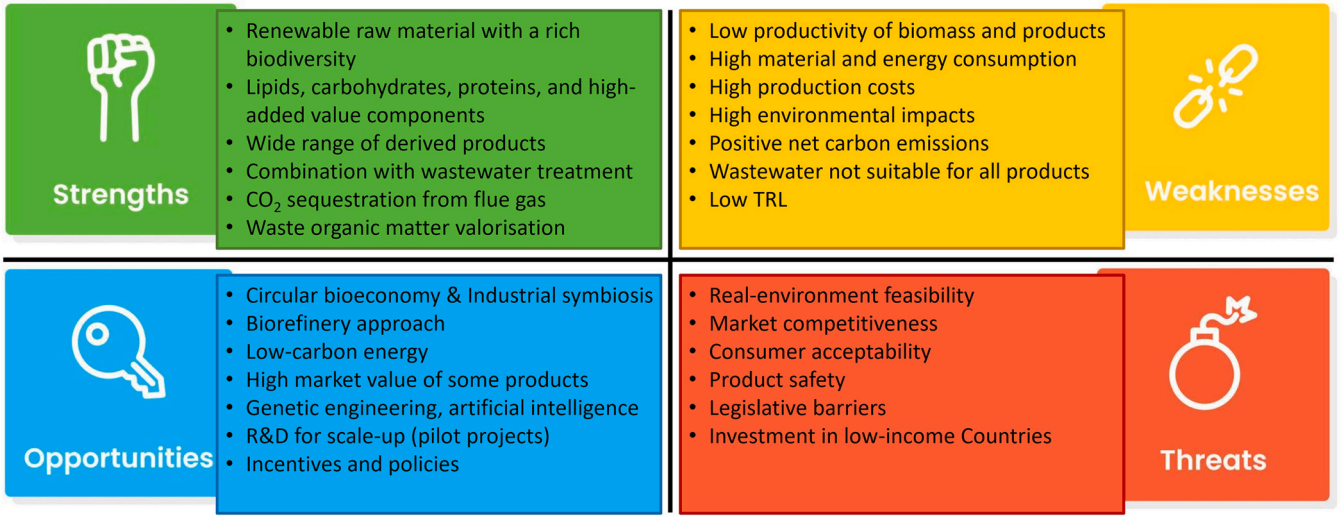

Fig. 9. SWOT analysis of sustainable microalgal industries.

incentives, and well-structured policies within a public-private collaborative network of academia, industry, and policymakers represent crucial enablers for shared infrastructure and risk mitigation. Targeted incentives such as carbon credits, subsidies, and tax breaks could significantly reduce financial barriers and attract early-stage investment. National biofuel policies, including feed-in tariffs and production mandates, offer templates to support algal biofuel pathways [150]. Several countries have implemented policy measures in the biofuel sector, but the offer of tax subsidies should be more substantial [151].

Several challenges and risks threaten the industrialisation of microalgal production systems. Many of the promising opportunities discussed in this review have to face the risk of poor feasibility in real environments, an aspect which still needs to be rigorously validated. A key barrier is the strong market competitiveness of conventional products, which presents a critical hurdle for the commercial success of many microalgal bioproducts. In parallel, consumer acceptability and product safety may represent other obstacles [152], at least for some microalgal bioproducts that may require long-term testing and certification, and they can significantly affect their demand [109] (for example, organoleptic characteristics in the case of novel foods [93]). Moreover, the microalgal industry faces significant legislative barriers deriving from regulatory fragmentation, which varies by region and product category [153] and results in overlapping issues, prolonged approval procedures, and considerable market uncertainty. The emerging bioeconomy is evolving within a complex policy landscape. Legislative barriers may regard the approval and regulation of novel food products, drugs, cosmetics, and biofertilizers [154]. For instance, the EU Novel Food Regulation mandates thorough safety assessments for novel foods before they can be marketed [155,156]. Regulatory complexity increases further when waste streams are used as cultivation medium [157] or when genetically modified algal strains are employed [158]. Other obstacles regard tariffs, labelling requirements, certifications, and regulated quality standards [159]. Moreover, many national biofuel mandates are narrowly defined around conventional feedstocks (corn, sugarcane, or oilseeds), thereby excluding microalgae from key bioenergy support schemes. The EU biofuels policy has lacked long-term consistency, marked by frequent shifts in priorities—from active promotion to consumption caps—creating uncertainty for investors and stakeholders [160]. While the aviation and maritime sectors have set long-term decarbonization goals, clear roadmaps are absent, and the future role of biofuels in road transport remains undefined [160]. Finally, the high costs of microalgae cultivation and bioproduct extraction demand large capital investments, posing a major barrier for innovators and hindering start-ups and emerging ventures, especially in low-income countries. In summary, without harmonized regulations, simplified procedures, a unified quality framework, and financial de-risking mechanisms in an enhanced business environment [161], the commercialization in the microalgal sector will remain slow and piecemeal.

5. Conclusions

This study presents a systematic meta-review of recent review articles that addressed the economic and/or environmental sustainability of microalgae-based production systems, assessed via TEA and/or LCA. A narrative synthesis was conducted alongside the homogenisation, detailed analysis, and interpretation of extracted quantitative data pertinent to selected performance metrics (production costs and GHG emissions). This approach enabled the identification of research trends, the development of a synoptic framework on the sustainability status of microalgal systems, including comparative analyses with conventional product benchmarks, the formulation of recommendations for future sustainability assessments, and the execution of a SWOT analysis.

Microalgae hold significant promise as feedstock for a wide array of bioproducts. However, current microalgae-based production systems are typically marked by low productivity and high consumption of materials and energy, resulting in high production costs and environmental impacts. Microalgal bioproducts tend to be uncompetitive both economically and environmentally compared to conventional products, and generally fall short of carbon neutrality. Despite this, results across all microalgal bioproduct categories are scattered over wide ranges and include optimistic scenarios. Only microalgal proteins exhibit competitiveness as a main trend, though this finding is based on a limited dataset. Two major strategies were identified as critical for improving sustainability performance: (i) the valorisation of waste streams in microalgae cultivation (e.g., wastewater bioremediation) and (ii) the biorefinery approach, which extracts the maximum value and distributes the environmental impacts. These strategies align with circular bioeconomy (resource effectiveness) and zero-waste (resource efficiency) paradigms and are pivotal drivers that should be further explored in the search for competitiveness and true sustainability. Additionally, low-carbon energy technologies and direct harnessing of sunlight provide improvements in overall GHG emissions. However, only a limited number of case studies were retrieved, and other environmental impact categories remain underexplored and require further analysis.

Pilot projects should be intensified to generate robust input data for reliable economic and environmental assessments, thereby guiding R&D

efforts toward the potential achievement of process maturity. In future sustainability assessments, a methodological harmonisation is highly recommended for facilitating comparative analyses. Nevertheless, this is a complex and multifaceted topic that requires significant effort. Furthermore, the current gap in comprehensive life cycle thinking approaches and multi-criteria optimisation should be bridged to assess and integrate all the sustainability dimensions and support the design of solutions that may be attractive to the market.

Essential opportunities for the microalgal industry may derive from a well-designed policy framework, including targeted incentives. However, the microalgal industry is currently facing substantial legislative barriers (fragmented regulations), insufficient investment, and slow standardisation. Other threats to real-world applicability derive from consumer acceptability and product safety. On the other hand, under well-supported, integrated conditions – combining technological innovation, harmonised policy support, and cross-sector collaboration – microalgae's sustainable potential may progressively evolve into a viable industrial reality.

Finally, we suggest conducting a comprehensive meta-analysis as a follow-up to the present study. By compiling a substantial dataset for each microalgal end-product from the extensive available literature, statistical analysis could enable a more robust quantification of average trends and appropriate management of uncertainty issues. However, such an undertaking would require significant effort and, hopefully, close collaboration among multiple research groups.

CRediT authorship contribution statement

Luigi Gurreri: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mirko Calanni Rindina:** Writing – original draft, Visualization, Validation, Investigation, Formal analysis. **Antonella Luciano:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Funding acquisition, Data curation. **Debora Fino:** Writing – review & editing, Writing – original draft, Validation, Supervision. **Giuseppe Mancini:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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