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REVIEW

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Benchmarking commercially available value-added fractions with potential for production via microalgae-based biorefineries: is it worth it?

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Abstract

The urgent need to mitigate climate change requires finding sustainable and efficient alternatives to fossil fuel-based materials. Biosequestration by microalgae has been suggested as a potential method for climate change mitigation due to its environmentally friendly nature and ability to produce high-value compounds. However, the large-scale application of microalgal biorefineries faces significant challenges, particularly in the harvest and processing stages, which are often costly and energy-intensive. This study aims to benchmark value-added fractions that can be produced via microalgae-based biorefineries against their commercially available counterparts. A systematic review was conducted using the Web of Science™ database to identify current commercial sources of proteins, lipids, polyunsaturated fatty acids and pigments, this study identified key sectors and applications for each fraction, as well as potential market competitors. The results highlight substantial cost differences across production systems, with traditional agricultural sources demonstrating lower CAPEX but greater environmental challenges. Meanwhile, microalgal systems, although associated with higher CAPEX, offer advantages such as reduced land and water dependency, potentially leading to long-term economic resilience and environmental sustainability. By pinpointing research trends, key sectors and optimization opportunities, this work offers valuable insights into the profitability and competitiveness of microalgal systems, providing a benchmark for future optimization efforts. The novelty of this research lies in its comprehensive comparison of microalgae-based and traditional production systems, establishing a clear benchmark for microalgal production and suggesting focus areas for enhancement.

Keywords Microalgal biorefineries, Value-added compounds, Techno-economic assessment, Life cycle assessment, Benchmarking and optimization

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Introduction

The primary driver behind current environmental research is the need to mitigate climate change. While much of this research focuses on atmospheric carbon sequestration, true mitigation can only be attained if the sources of these emissions are reduced or eliminated. This effort requires finding sustainable and efficient alternatives to fossil fuel-based materials. Despite significant advancements in carbon sequestration technologies, the challenge remains in identifying scalable, cost-effective and environmentally sustainable solutions that can replace conventional fossil-based products. Atmospheric carbon sequestration by biological organisms, or biosequestration, has been suggested as a potential method for climate change mitigation. However, while biosequestration is an attractive alternative, its large-scale application remains constrained by economic and technical challenges [1]. Microalgae have emerged as one of the most promising biological organisms capable of performing biosequestration under the appropriate growth conditions. These microorganisms are a highly versatile type of biomass, able to be cultivated in various water sources (saline waste, wastewater) and growth conditions (heterotrophic, autotrophic, mixotrophic) without competing with other types of cultures for arable land [2]. Furthermore, when grown under heterotrophic and mixotrophic conditions, selected biological residues (e.g., forest residues, wheat straw, food waste) can be used as carbon and energy sources instead of the more commonly used commercial glucose or xylose [3]. They are also composed of valuable biomolecules such as lipids, proteins, carbohydrates, and other bioactive compounds, making them suitable for nutritionally dense applications in human and animal health products. Microalgae are especially prized for their high concentrations of essential nutrients, antioxidants, and omega-3 fatty acids, among others, which support immune function and disease prevention, enhancing their appeal for sustainable industry applications [4]. In animal feed, especially for aquaculture, microalgae serve as efficient nutrients sources, reducing reliance on traditional feedstocks, being naturally part of the food chain as the lowest trophic level. Additionally, their bioactive components contribute to the cosmetics and pharmaceutical industries, leveraging antioxidant and anti-inflammatory properties [5].

As previously stated, microalgae can be grown through various growth patterns and associated cultivation systems. Open raceway ponds and closed photobioreactors are among the most common systems for autotrophic cultivation. The former tend to be less expensive in terms of capital expenditure (CAPEX) but are susceptible to contamination and environmental fluctuations, while the latter offer controlled environments for higher biomass yields but may come at greater CAPEX and operational expenditure (OPEX) depending on technology, method and final product [6]. Mixotrophic and heterotrophic growth is generally undertaken in closed bioreactors, allowing for more consistent production but requiring often expensive organic carbon inputs [7].

Despite these advantages, the principal problem with the large-scale application of microalgal biorefineries is linked to the harvest and processing stages that succeed the initial production [8]. While the concentrations and characteristics of heterotrophically grown microalgae make it relatively simple to separate the intervening fractions, the same cannot be said for autotrophic cultivation. The high water content and relatively low biomass concentrations (approximately 1 g biomass per L) in autotrophic systems make harvesting processes long, expensive and energy intensive, thus hindering commercial feasibility [9]. According to Lam et al., the harvest and processing stages of a microalgal biorefinery can account for approximately 20–30% of the total OPEX, with energy expenditure being one of the major contributors [10]. Furthermore, Collet et al. affirm that energy requirements for algal biofuel production can offset its carbon sequestration benefits unless renewable energy sources are integrated into the production chain [11]. A comprehensive assessment of techno-economic and environmental constraints is, therefore, essential to optimize the viability of microalgal biorefineries.

As seen above, the production methodology and its bottlenecks are already well defined in the literature, with a vast body of work examining the various components of the system and associated optimization routes. However, the key challenge remains in determining whether products derived from microalgae can effectively compete with those already available on the market. A holistic comparison of economic and environmental performance between microalgal-based products and conventional counterparts is still lacking in the literature. This competition must consider not only economic factors—though production costs will undoubtedly play a significant role in decisions by stakeholders (value-chain actors, consumers and society at large)—but also environmental and social dimensions.

The present study focuses on the recovery of techno-economic and environmental data of the established production systems whose products can be replaced by microalgal-based compounds. Table 1 summarizes the microalgae species most commonly considered as basis for biorefineries. The primary goal of this work is to conduct a detailed literature review to identify and evaluate the primary bottlenecks in these systems, analyzing their environmental and economic characteristics as well as optimization options before comparing them to microalgal products whenever appropriate. The environmental assessment will focus on the analysis of the global warming potential (GWP) of each method due to the prevalence of its quantification in environmental studies. The economic comparison will focus on OPEX and CAPEX, assessing how microalgae production systems measure up against traditional methods in terms of cost-effectiveness and scalability. By integrating these perspectives, this research aims to provide valuable insights into the feasibility and sustainability

Table 1 Key microalgae species for biotechnology industries and potential applications

Species	Compounds	Application	References
Arthrospira (Spirulina) *platensis*	Phycocyanin, Lipids, Protein	Health food, cosmetics, pharmaceuticals	[12]
Arthrospira (Spirulina) *maxima*	Phycocyanin, Lipids, Protein	Health foods, cosmetics, pharmaceuticals	[13]
Botryococcus braunii	Lipids, Hydrocarbons	Biofuel production, cosmetics	[14]
Chlorella sorokiniana	Lipids, Protein	Health foods, dietary supplements, and feed substitutes	[15]
Chlorella vulgaris	Lipids, Protein	Health foods, dietary supplements, and feed substitutes	[16]
Chlorella kessleri	Lipids, Protein	Health foods, dietary supplements, and feed substitutes	[17]
Desmodesmus vacuolatus*	Lipids, Protein	Health foods, dietary supplements, and feed substitutes	[18]
Desmodesmus obliquus*	Lipids, Protein	Health foods, dietary supplements, and feed substitutes	[19]
Dunaliella Salina	Carotenoids, β-carotene	Health foods, dietary supplements, feed	[20]
Haematococcus pluvialis	Carotenoids, Astaxanthin	Health foods, pharmaceuticals, feed additives	[21]
Nannochloropsis oceanica	Lipids, Fatty acids (Omega-3)	Pharmaceuticals, cosmetics, dietary supplements	[22]
Nannochloropsis gaditana	Lipids, Fatty acids (Omega-3)	Pharmaceuticals, Cosmetics, dietary supplements	[23]
Tetraselmis chuii	Lipids, Protein	Aquaculture feed, biofuels	[24]

*Formerly *Scenedesmus*

of microalgal biorefineries, paving the way for future advancements in bio-based industries.

Materials and methods

Search strategy and query implementation

A systematic search methodology was followed, based on the method utilized by Pacheco et al. [25]. A comprehensive search was conducted using the Web of Science™ database (www.webofscience.com), accessed on December 2, 2023, to retrieve relevant academic publications for the period of January 1, 2013, to December 1, 2023. Zotero version 6.0.36 was employed for literature management and initial abstract screening. Data extraction and management were performed using Microsoft® Excel®, facilitating the sorting and analysis of the collected data based on predefined categories including: ID, reference, production scale, data source (theoretical or in situ), year of study, data type (qualitative or quantitative), functional unit (FU), capital expenditure (CAPEX), operational expenditure (OPEX), price per kg of product, GWP, other pollutants released, product, final use and strain/species. A preliminary literature analysis identified four microalgal products of commercial importance: protein, pigments, tryacylgycerides (such as eicosapentaenoic acid (EPA) or docosahexaenoic acid (DHA)) and polyunsaturated fatty acids (PUFA). These compounds were considered for the formulation of four search queries and employed as follows:

- Query (a): Author keywords: *("Techno-Economic" OR "LCA" OR "life-cycle" OR "life cycle") AND* All fields: *("protein*")*
- Query (b): Author keywords: *("Techno-Economic" OR "LCA" OR "life-cycle" OR "life cycle") AND* All fields: *("Phycocyanin" OR "pigment*" OR "carotenoid*")*
- Query (c): Author keywords: *("Techno-Economic" OR "LCA" OR "life-cycle" OR "life cycle") AND* All fields: *("Lipid" OR "Total fatty acid" OR "triacylglycerides*")*
- Query (d): Author keywords: *("Techno-Economic" OR "LCA" OR "life-cycle" OR "life cycle") AND* All fields: *("omega-*" OR "PUFA")*

The various queries considered solely articles written in the English language as to maintain consistency in data interpretation. To avoid duplication, the search excluded review articles. Initial data search yielded a total of 1586 articles, which were then subjected to further screening based on predefined exclusion criteria.

Screening criteria and data normalization

To streamline the management and review process of the collected literature, Web of Science™ data was converted into.*ris* files, ensuring integration with Zotero for systematic organization, reference annotation and removal of duplicates prior to the screening stage. Studies were discarded from the analysis group according to the following exclusion parameters: study (1) did not include any of the 4 considered category products (pigments, polyunsaturated fats, proteins and lipids), (2) did not include techno-economic assessment or (3) did not include environmental assessment. Studies developed at a laboratorial level or with limited study boundaries (gate-to-gate) were discarded. The secondary screening stage eliminated processed feedstocks (e.g., processed food) and optimization studies, which would include additional processing stages and non-comparable functional units.

Techno-economic data were converted to a common currency (€, Euro) using the exchange rate applicable in the year of the study with data sourced from World Bank [26]. CAPEX per kg was calculated through Eq. 1.

$$\mathrm{CAPEX}_a = \mathrm{CAPEX}_b \times \left(\frac{\mathrm{Capacity}_a}{\mathrm{Capacity}_b}\right)^{0.60} \quad (1)$$

where $\mathrm{CAPEX_a}$ represents the original CAPEX (€), $\mathrm{CAPEX_b}$ is the CAPEX per 1 kg adjusted (€), $\mathrm{Capacity_a}$ is defined as 1 kg/year and $\mathrm{Capacity_b}$ is the annual production reported (€). The six-tenths factor rule (exponent 0.60) was applied as a generalist conversion value applicable to the various industries under analysis [27]. The production cost per kg was calculated by dividing the OPEX values per annual production. All environmental data was converted into "impact category unit" per mass of product (i.e., 1 kg of the selected product) to allow direct comparison between systems.

Results and discussion

Literature screening

The systematic review was elaborated according to the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) methodology. This document reports the necessary guidelines for the identification, selection, appraisal and synthetization of literature documents, including the various stages related to the purpose behind the elaboration of the study, its aim and primary conclusions. The flow diagram for this systematic review is represented in Fig. 1, illustrating the appropriate

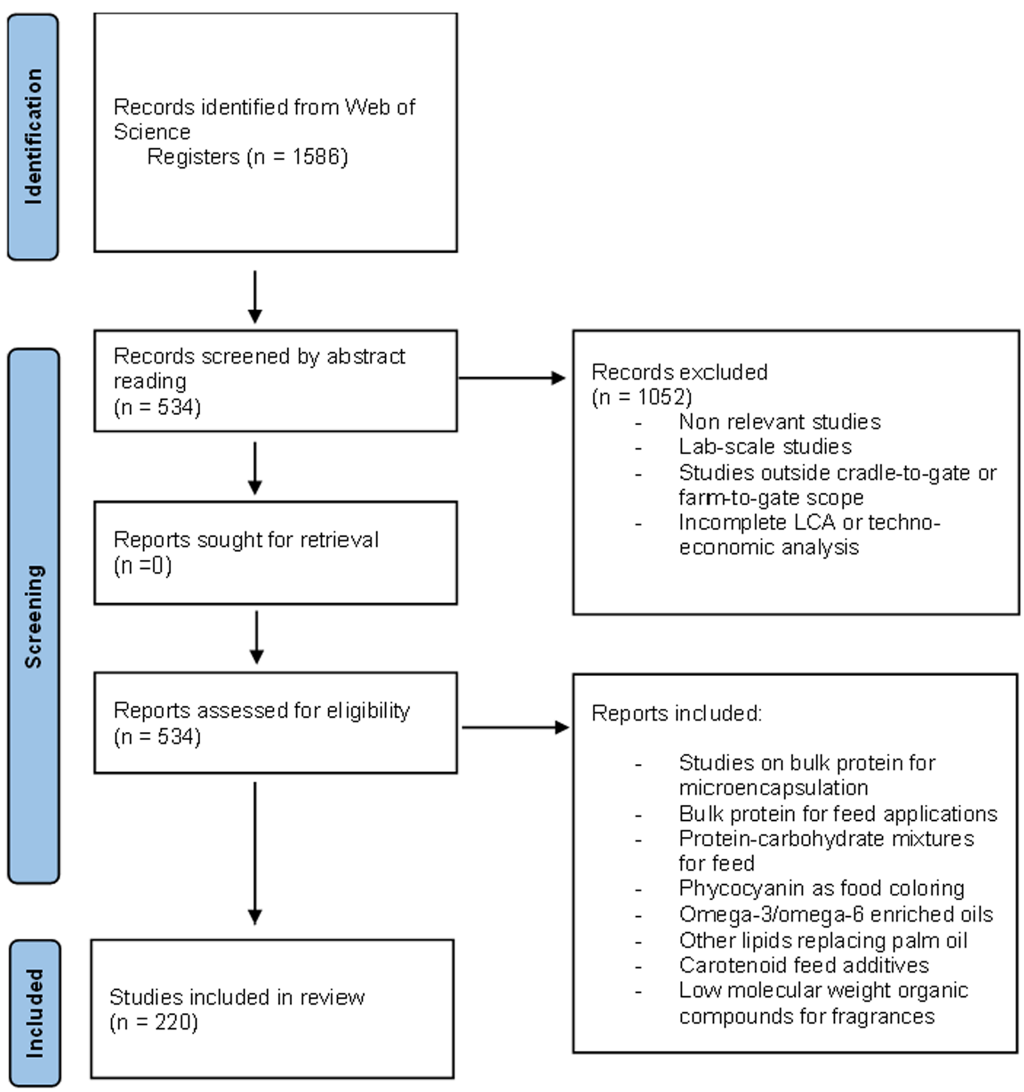

Fig. 1 Flow diagram of the systematic review undertaken in this study according to the PRISMA 2020 methodology

methodology stages and the various parameters for study inclusion/exclusion (based on Prisma, [28]). The identification, screening and inclusion stages yielded a total of 1586, 534 and 220 articles, respectively, the latter of which used for the elaboration of the in-depth analysis.

The final screening resulted in a total of 220 articles for analysis, which were then grouped according to the nature of their final products or FU:

- Bulk protein for microencapsulation of fragrance ingredients (at least 80% protein content);
- Bulk protein for animal and vegetable protein replacement in feed applications (60–80% protein content);
- Bulk protein and carbohydrates mixtures for feed applications;
- Protein-pigment complex phycocyanin or pure phycocyanin extracts for natural food coloring;
- Omega-3/omega-6 fatty acid (including eicosapentaenoic acid, EPA and docosahexaenoic acid, DHA) enriched oils for fish oil replacement in feed and edible spreads;
- Other lipids including triacylglycerides and phospholipids for palm oil replacements in edible spreads;
- Carotenoid feed additives, including beta-carotene, for improvement of animal health or as pigment (e.g., egg yolk);
- Other pigments with potential use in feed, food or nutraceuticals.

The number of articles and entries considered in the review for techno-economic data and carbon footprint are detailed in Table 2. It is important to underline that various articles propose alternative scenarios, contributing to more than one impact value for the same type of production, i.e., the number of articles is often different from the number of impact values considered (or entries).

Table 2 Number of articles and entries used for average value calculation

Final product	Analysis	Nr. of articles	Nr. of entries
Pigments	Techno-economic	8	27
	Environmental	14	30
Polyunsaturated fatty acids (PUFAs)	Techno-economic	3	4
	Environmental	9	16
Lipids	Techno-economic	14	31
	Environmental	12	24
Protein	Techno-economic	17	31
	Environmental	105	210

Bibliographical data and trend analysis

To establish the environmental and techno-economic targets of a potential microalgal biorefinery, a cursory analysis of the publication trends of the four main microalgal products was performed. Figure 2 illustrates the research publication trends in the techno-economic assessment (TEA) and life cycle assessment (LCA) fields within the pigment, lipids, protein and polyunsaturated fatty acids (PUFA) industry from 2013 to 2023.

The data in the graphical representation reflect a growing interest in sustainable practices and economic evaluations in industrial processes, marking a foundational period when the significance and application of these studies were first recognized. There seems to be an increasing trend from 2016 onwards on the number associated to these types of publication, one which was interrupted in the 2019–2020 period, likely due to the influence of the COVID-19 pandemic, which disrupted research activities worldwide and causing delays in publication schedules. Additionally, the economic uncertainties and logistical challenges posed by the pandemic may have led to reduced research outputs during this period [29]. The end of this period saw a return to the previous trend, reflecting an ongoing worry with the impact of established production systems and highlighting the pivotal role of these studies in informing policy and decision-making processes [30]. The analysis of the collected data revealed significant challenges. A commonality across the entire body of work lay in the lack of data standardization, varying greatly in presentation format, production scales and units. This inconsistency in data presentation is a common obstacle in LCA studies, as highlighted by Cliff and Druckman, and complicates the comparison between the various published results [31]. Ultimately, only 80% of the identified studies provided data suitable for quantitative analysis.

The vast majority of the published studies seem to focus on the analysis of already established large-scale facilities in an apparent drive to identify production hotspots and suggest optimization routes to decrease costs or energetic expenditure. Figure 3 depicts the frequency of different species groups used for various product goals in the selected body of work, i.e., it represents the most common source for each use (food, feed and nutraceuticals).

In terms of food production, farm animals are the most frequently used species group, indicating a strong reliance on traditional sources of food and reflecting established cultural and agricultural practices for food production. Plants and fish were identified as frequent alternatives for supplementary food sources, with a recent small encroachment of microalgal. Insects and worms, however, are considered to a much lesser extent,

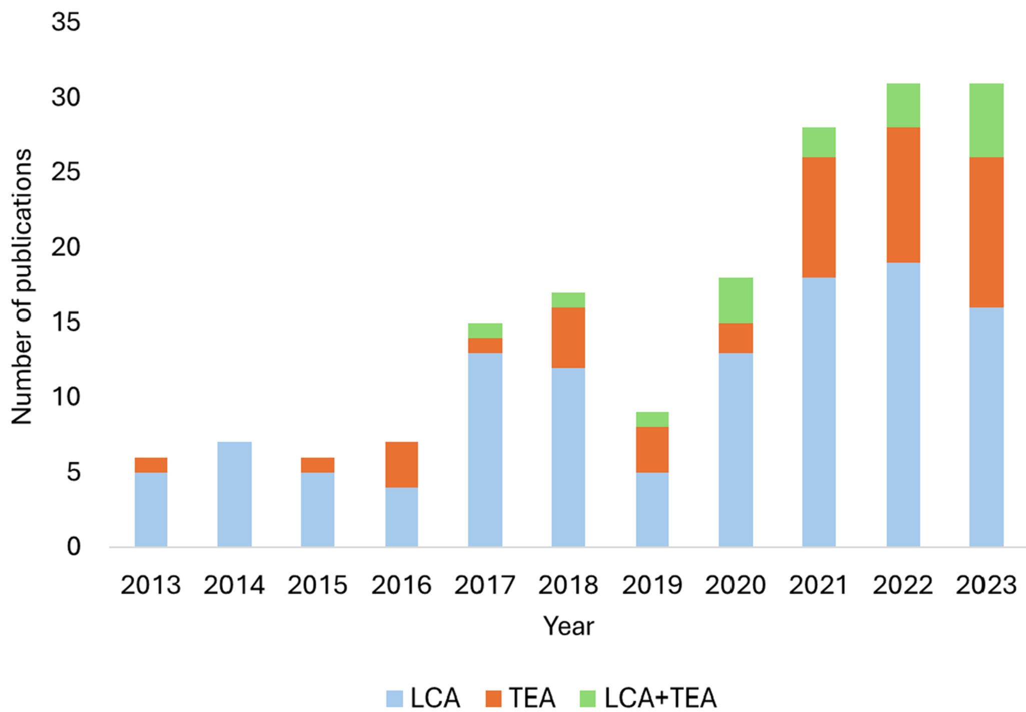

Fig. 2 Number of publications related to the life cycle or techno-economic assessment of the defined groups of interest for the period of 2013–2023

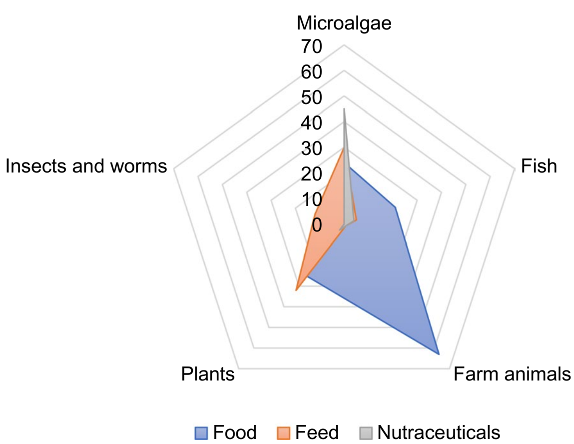

Fig. 3 Radar representation of final product publication frequency (Food—blue; Feed—orange; Nutraceuticals—green) per species group

probably due to cultural differences or health concerns. Conversely, in the context of feed products, plants and microalgae are the major production sources, indicating their primary role in animal feed formulations. The steady increase in use of insects and worms in this area is notable, suggesting emerging trends due to their high protein content, nutritional value (i.e., higher and cheaper protein), and potentially lower environmental impacts of their production processes. Nutraceuticals production is clearly associated to microalgae production and processing, a preference probably related to the presence of naturally occurring bioactive compounds, many of them with recognized health benefits. Plants, fish, and farm animals are barely considered, while insects and worms are not referenced for this use [32]. Concluding, there is a clear evolution on the types of species utilized as feedstock for each product, varying due to environmental and health concerns while being hampered by the economic fragility displayed by newer production solutions. These trends reflect the broader shifts towards sustainability, innovation, and practical impact in industrial research and applications [33].

Quantitative analysis

Techno-economic assessment

- *Pigments*

  The economic analysis of various pigment production methods highlights the intricate relationship between production costs, market demand, and profit margins. Figures 4, 5 and 6 provide valuable insights into these dynamics by visually representing key economic indicators and their impact on pigment production.

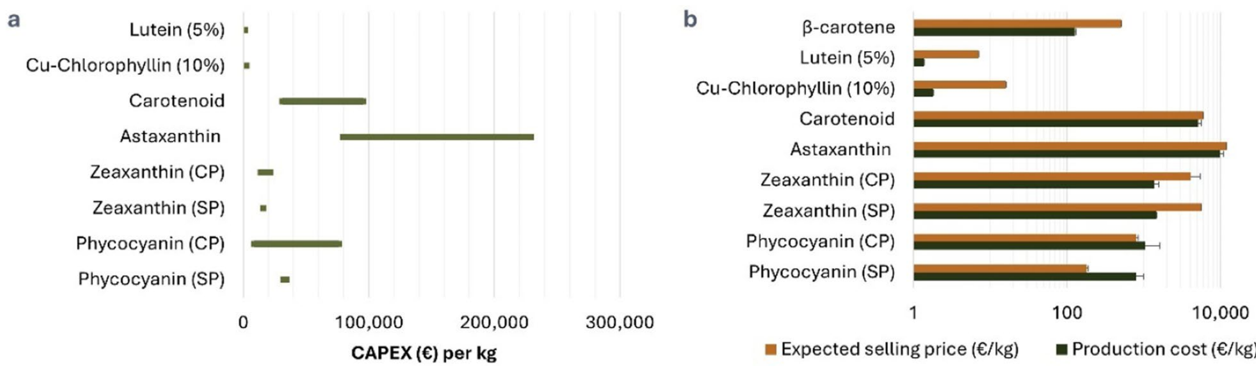

Fig. 4 **a** CAPEX per kg for different pigment production. SP–single production, CP–co-production; **b** Expected selling price (€ per kg) and production cost (€ per kg, blue) for different pigment productions

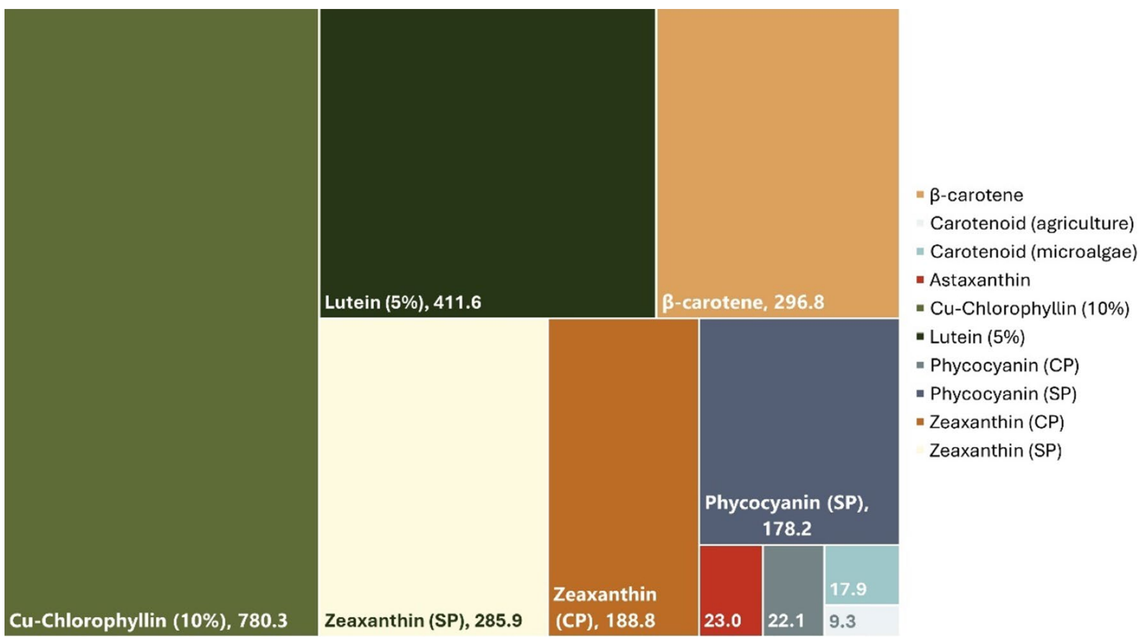

Fig. 5 Profit margins for different pigments production, in percentage (%). SP–single production; CP–co-production

Figure 4a further illustrates the financial challenges in pigment production by showing the CAPEX per kilogram for different production processes. The comparison reveals the financial burden of microalgae-based pigment production, especially for pigments such as food-grade astaxanthin and phycocyanin, which require additional specialized equipment for compound separation and purification from the biomass, resulting in higher CAPEX [34]. Figure 4b compares the expected selling price per kilogram (€/kg) and the production cost per kilogram (€/kg) for various pigments. Microalgae-derived pigments such as astaxanthin and zeaxanthin command significantly higher selling prices, largely due to their health benefits, such as antioxidant properties and potential roles in eye health [35]. On the other hand, pigments from agricultural sources have lower production costs, mainly because of established farming techniques that increase pigment yield and concentration. However, these agricultural pigments typically have lower purity levels, which limits their use in high-value markets like pharmaceuticals, resulting in lower profit margins [34]. Figure 4b demonstrates that, despite higher production costs, microalgae-derived pigments can still be economically viable due to their ability to command premium prices in specialized markets. In a study by Pinto et al. [36], a high-pressure extraction method using supercritical CO_2

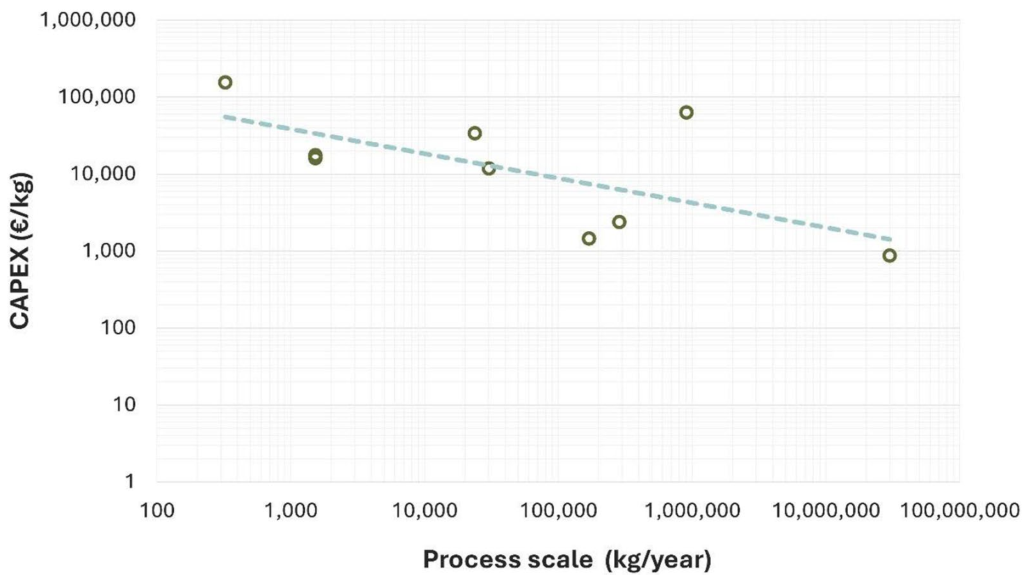

Fig. 6 Relationship between annual production volume and CAPEX per kilogram of product, for various pigment production methods

and ethanol was employed to extract lipids and phycocyanin from *Arthrospira platensis* (Spirulina) [36]. The supercritical CO_2 extraction process yields a product with higher purity and fewer contaminants, making it highly sought after in pharmaceutical and high-end nutraceutical markets. This characteristic leads to a commercial value of approximately 432 €/kg, a value well above the necessary to offset the high production costs and CAPEX, 86.2 and 31,482.7 €/kg, respectively, driven by the need for high-pressure systems, substantial energy use, as well as CO_2 capture and recycling to minimize environmental impact and operational expenses [36]. In contrast, a study by Ferreira da Silva et al. [37] explored the use of a genetically modified strain of *Synechocystis* for the production of phycocyanin and ethanol [37]. This method has a much lower CAPEX of 803.8 €/kg and a production cost of 64.2 €/kg. The lower economic input requirements are attributed to the use of membrane filtration for harvesting and ultrasonication for cell disruption, which are more energy-efficient and less capital-intensive than high-pressure systems. Furthermore, the concurrent production of ethanol provides an additional revenue stream, helping to compensate the production costs. The expected selling price for this approach is 190.1 €/kg per kilogram, which, although lower than that obtained through the method by Pinto et al., is better suited for broader market segments where ultra-high purity is not a critical requirement [36]. The stark contrast in selling prices highlights the differing market positions and value propositions of the final products.

Figure 5 analyzes the profit margins for various pigment productions. Pigments, such as lutein and Cu-chlorophyllin, achieve favorable profit margins despite being produced through relatively low-cost methods, suggesting that market demand plays a crucial role in profitability—pigments with higher demand can yield substantial profit margins even if their production costs are lower [38, 39].

Figure 6 presents a log–log plot illustrating the relationship between annual production volume and CAPEX per kilogram of product for various pigment production methods. The trendline indicates an inverse correlation between production volume and CAPEX, suggesting that as production volume increases, the CAPEX per kilogram decreases. This observation aligns with the concept of economies of scale, where larger production volumes lead to more efficient use of resources and cost distribution, reducing per-unit costs [40]. The data reinforce the idea that scaling up production can improve economic feasibility, particularly for high-demand pigments, where large-scale production helps offset high initial CAPEX.

Despite the high production costs associated with microalgae-derived pigments, the data demonstrate their economic viability in markets where product purity and efficacy are prioritized. For example, although pigments like astaxanthin and phycocyanin are costly to produce, their high selling prices and strong market demand in specialized sectors ensure their profitability [41]. Furthermore, the inverse relationship between production volume and CAPEX, as shown in Fig. 6, suggests that increasing production volumes could enhance economic outcomes by reducing the CAPEX per unit through more efficient production processes. Despite the high production costs associated with microalgae-derived pigments, the data demonstrate their economic viability in markets where product purity and efficacy are prioritized. For example, although pigments like astaxanthin and phycocyanin are costly to produce, their high selling prices and strong market demand in specialized sectors ensure their profitability [41]. Furthermore, the inverse relationship between production volume and CAPEX, as shown in Fig. 6, suggests that increasing production volumes could enhance economic outcomes by reducing the CAPEX per unit through more efficient production processes. These results indicate that while the production costs for microalgae-derived pigments are high, their profitability is supported by strong market demand, premium pricing in specialized sectors, and the potential benefits of economies of scale. Therefore, the economic feasibility of these pigments depends on strategic production scaling and market positioning to capitalize on demand for high-quality, high-efficacy products.

- *PUFAs*

  The search query used in this study did not yield a large quantity of articles focused on PUFAs TEA compared to the remaining considered products. This is likely because PUFA production, particularly through reduction fisheries, is a well-established method that does not appear to be a primary focus for further optimization in the scientific community. Reduction fisheries target small, oily fish species such as anchovies, sardines, and menhaden, which are primarily processed into fishmeal and fish oil. These by-products are widely used in animal feeds, including aquaculture, and are key sources of omega-3 fatty acids. Additionally, these fisheries play an important role in waste management by processing by-products and waste from other fisheries, which enhances their overall sustainability [43]. Economic assessments of PUFA production indicate that standalone production is not economically viable due to high production costs [42]. The costs range from 7.95 to 19.03 €/kg, while the expected selling prices are much lower, approximately 1.59 €/kg, resulting in negative profit margins [44]. However, PUFA production becomes economically feasible when integrated into co-production systems. For instance, as demonstrated by Sawaengsak et al. 1 profitability can be enhanced by producing both biodiesel and PUFAs simultaneously [44]. Despite this, the increased CAPEX and OPEX associated with PUFA purification presents significant economic challenges that could deter profitability. An alternative approach for improving the economic viability is to utilize less refined forms of PUFAs for simpler uses, such as in animal feed, where high purity is not a requirement. By eliminating refinement stages like product purification, the process inputs and subsequent production costs are reduced, making the process more economically sustainable [45]. This approach aligns with broader sustainability goals by minimizing waste and reducing reliance on unsustainable sources, such as reduction fisheries, which face limitations due to overfishing pressures [46].

  The co-production approach has also been considered within the microalgae sector, which generally ascertains that the single production cannot offset the significant CAPEX and OPEX values, particularly those related to the extraction and purification stages [47, 48].

- *Lipids*

  Techno-economic assessments of lipid production highlight significant differences in the economic viability of various production methods (Fig. 7). Lipids derived from microalgae, insects, mammalian cells, and traditional sources like milk and meat farms each exhibit distinct cost structures based on their production processes and end applications.

  The analysis shows that oil production, particularly from microalgae, is substantially more expensive than other lipid production methods, primarily due to higher CAPEX and OPEX. This is due to the complex infrastructure and stringent quality control measures required to meet regulatory standards for food and biofuel applications [49, 50]. Simpler lipid production methods, such as those used in milk and meat farms, require lower initial investments and operational costs due to their more straightforward processes and scalable technologies. These methods offer cost-effective solutions for large-scale production, especially when established agricultural practices are leveraged. In contrast, newer methods, such as mammalian cell-based production, are still in the research phase and are not yet widely adopted in the industry due to uncertainties surrounding safety, regulatory approval, and scalability [51]. When comparing CAPEX (Fig. 7a) for meat production and microalgae, there are notable differences in production methods and costs. Taking a study by Pinto et al. as an example, the focus on food-grade lipid production from microalgae required the use of advanced extraction methods such as supercritical CO_2 and

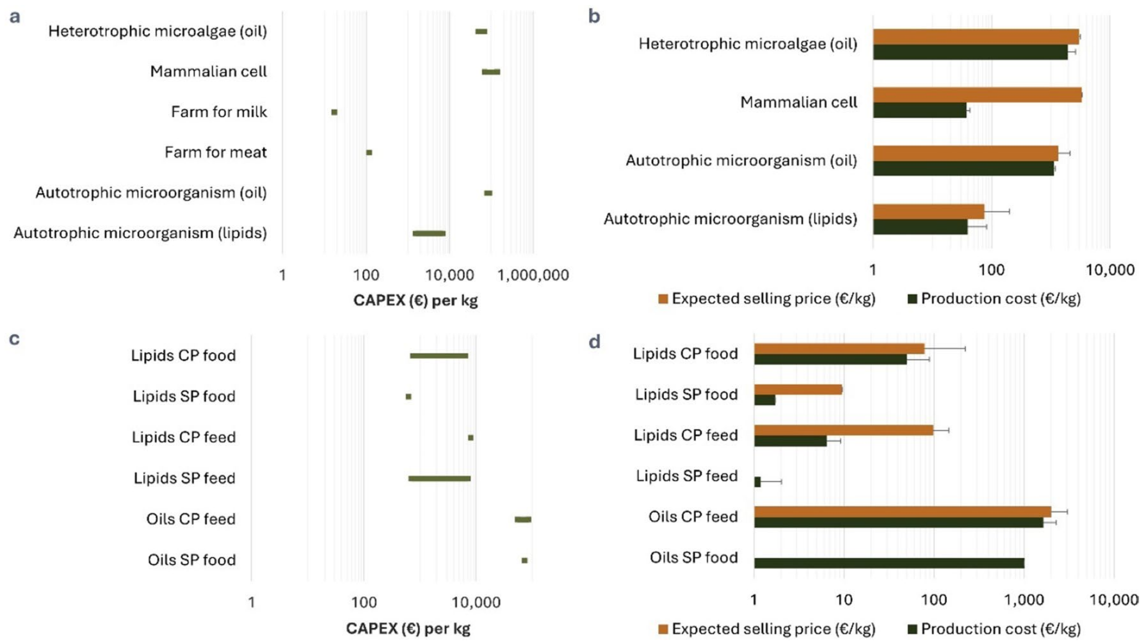

Fig. 7 CAPEX per kg **a** and price of production per kg with expected selling price **b** adjusted by product origin for lipid production. CAPEX per kg **c** and price of production per kg with expected selling price **d** adjusted by type of production and final use for lipids. SP–single production; CP–co-production

high-pressure ethanol extraction [36]. While these methods are highly efficient, they require substantial energy inputs and expensive equipment, significantly driving up production costs (CAPEX of 624.1 €/kg for single lipid production). Conversely, assessments performed with data from meat production, which generally integrate meat and milk production, report much lower CAPEX values (118.1 €/kg) [52]. This cost-effectiveness is attributed to the co-production model, which allows for more efficient resource use and cost-sharing between different products. Furthermore, while meat production may have environmental benefits, such as lower feed production costs, improved animal welfare, and reduced reliance on off-farm inputs, the economic viability of such systems is sensitive to market conditions and input costs, especially in highland regions, where input prices are higher, and output prices are lower [52]. When examining the economic viability across different end-use categories, lipid production for food applications consistently shows the highest costs. This is driven by rigorous quality control requirements, regulatory compliance, and high market demands for product attributes such as purity, taste, and texture [53]. In contrast, lipid production for feed applications exhibits the lowest costs, aligning with industry expectations for cost-effectiveness in feed markets where less stringent quality standards and lower raw material costs reduce overall expenses [54]. This data support the statement that investments in lipid production technologies will vary significantly based on the intended end use [55]. As lipid production technologies, particularly microalgae-based systems, continue to evolve, ongoing optimizations are expected to reduce costs and enhance sustainability, reinforcing their potential in the global market.

- *Proteins*

  The TEA of protein production methods reveals significant differences in cost structures and economic viability across various production technologies (Fig. 8).

  As observed in the previous section, traditional agricultural sources such as meat and dairy, have relatively low CAPEX compared to biotechnological methods regardless of the product considered. As observed in the previous sections, the characteristics of the obtained products, particularly the purity of the material, drives its intended use, demand and associated profit [56]. Dairy and meat farming demonstrates the lowest CAPEX among the methods analyzed, thanks to its simpler technology that allows for efficient protein production without the need for significant capital investment in complex equipment [57, 58]. Zira et al. assessed the economic viability of traditional livestock farming systems in Southwest-

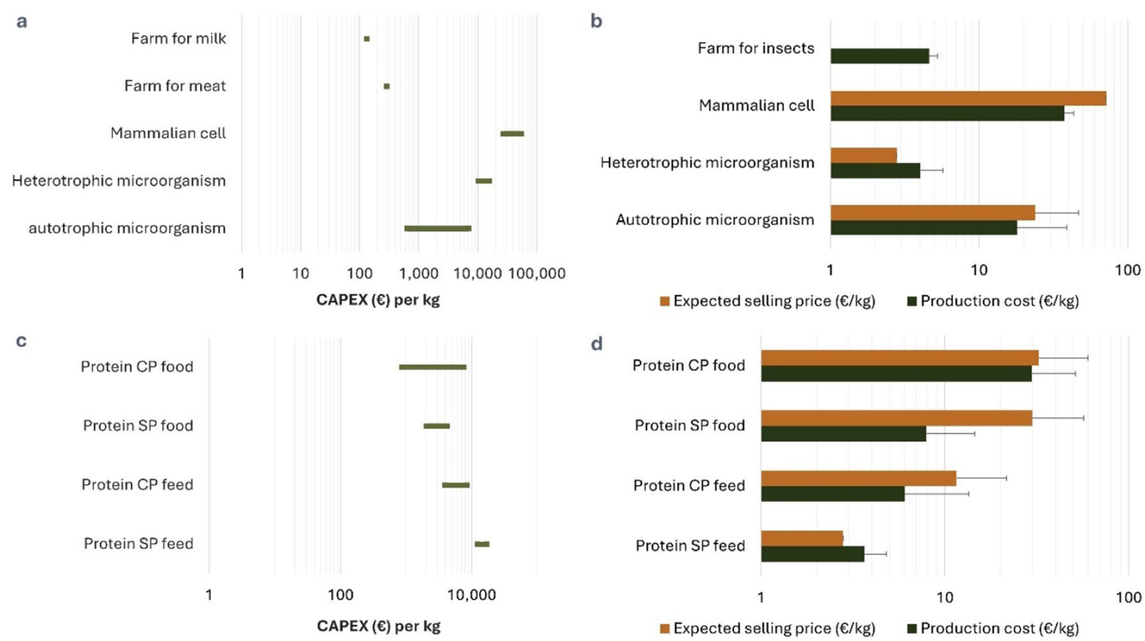

Fig. 8 CAPEX per kg **a** and price of production per kg with expected sell price **b** adjusted by product origin for protein production. CAPEX per kg **c** and price of production per kg with expected sell price **d** adjusted by type of production and final use for proteins. SP–single production; CP–co-production

ern Europe and reached the CAPEX values of 288.78 €/kg and 132.5 €/kg of protein from the meat and dairy industry, respectively [52]. These costs reflect the capital needed for land use, feed production, and maintenance of dairy and beef operations. The study also finds that cattle systems utilizing semi-natural pastures, particularly in highland regions, have lower environmental impacts in terms of land use and feed-food competition compared to more intensive farming systems. However, these systems are also more susceptible to economic volatility, such as fluctuations in feed costs and market prices for meat and milk. In contrast, biotechnological methods, particularly those involving autotrophic and heterotrophic microorganisms, consistently reached higher CAPEX and OPEX due to the need for specialized infrastructure, controlled environments, and specific feed inputs, often requiring large-scale bioreactors and costly harvesting systems. These can be potentially diminished by the use of non-arable land, non-potable water sources, or even drinkable water sources with much lower input, reducing competition with traditional agriculture and enhancing sustainability [59]. It is important to note, however, that the use of such water sources may introduce contaminants or particulates that could complicate downstream processing. These potential gains due to operational optimization are responsibly by the characteristic data variability [59]. The most favorable CAPEX result for microalgae-based biorefineries identified in this study reached a minimum value of 509.29 €/kg of protein produced, approximately 4 times higher than traditional protein production [60], even when considering the co-production of various bioproducts, including proteins, pigments, and renewable fuels. This high CAPEX is attributed to the complex processes involved in cultivating and extracting high-value products from *Chlorella* sp. in a cascaded biorefinery setup, which includes sequential saponification steps to maximize protein yield. OPEX improvements can be achieved through optimized growth modes, such as using carbon-rich industrial waste streams for heterotrophic cultivation or nutrient-rich wastewater for autotrophic growth [61, 62]. The choice of an industrial context over another, if necessary, should take other aspects into consideration, particularly those related to the environmental and social settings. As example, while traditional cattle farming benefits from lower CAPEX values, it might be associated to greater environmental challenges, such as methane emissions, land degradation, and feed-food competition. [63]. Conversely, cattle farming continues to be economically viable in regions with established agricultural practices and integrated local ecosystems.

Single production systems for feed (SP Feed) demonstrate the lowest OPEX among all categories, primarily due to its use of biological residues as the main feedstock, a characteristic that significantly reduced raw material procurement expenses. Co-production methods for feed (CP Feed) benefit from shared infrastructure, resulting in lower CAPEX, but exhibit moderate OPEX due to the complexity of managing multiple production streams [55]. This balance between low cost and moderate profitability makes CP Feed a steady, if not highly lucrative, option for protein production, with a high profit margin of 563.8%. Both co-production (CP Food) and single production (SP Food) for food applications exhibit similar CAPEX and expected selling prices. However, the key difference lies in production costs: CP Food averages 29.8 €/kg, while SP Food is significantly lower at 7.9 €/kg. This gives SP Food a much higher profit margin, though CP Food likely offsets its lower margin through additional product streams.

Carbon footprint

As a complement to the previous section, it is necessary to identify the various competitors to microalgal products and formulate a benchmark where it comes to its environmental performance. Considering the wide range of assessments available, a conscious decision was made during the development of this study to focus on the quantification of the climate change category (kg CO_2 eq. per kg of product). The data associated with the production of each fraction type are depicted in Table 3, including already published data related to current microalgal production.

- Pigments

The bibliographical data in relation to pigment production had severe limitations due to the limited number of studies which perform the complete environmental analysis of this type of production. The query itself might have excluded relevant studies which consider pigment production but categorize them under different nomenclatures such as: vitamins, supplements or nutraceuticals. As seen in Table 3, most of its production is associated to autotrophic microalgae development (particularly carotenoid pigments) where these compounds are generally produced as a stress response by the microorganisms (ex: exposure to light [64]). A small pigment minority can also be obtained through the metallurgic industry (undefined green pigment) and agriculture (anthocyanin). Furthermore, out of the 8 pigments identified in this study, 5 were referenced by a sole study and, due to that particularity, will not be considered in further analysis. Of the remaining 3, while the type of production has similar operational characteristics (i.e., solar dependent associated atmospheric carbon consumption), the variation in the choice of bioreactor, carbon addition methodology, light distribution or pigment accumulation will cause visible differences in the environmental impact results. Of the various pigments, only β-carotene and phycocyanin were considered by a minimum of 6 studies, with climate change values oscillating between similar orders of magnitude. This effect and the similar results attained in the studies related to carotenoids, a-tocopherol and phycobiliprotein lead to the assumption that quantified impacts are more dependent on the manner of production, rather than the type of obtained pigment.

Table 3 Global warming potential values associated to the 4 selected fractions obtained from the various industrial sectors

Product	Lipids	PUFA	Pigments	Protein
$kgCO_2eq$ per kg of product				
Source				
Autotrophic microalgae	0.5–668.2	172.1–7649.6	17.9–17,663.6	−0.02–404.3
Heterotrophic microalgae	94.5	4.1–4000.0	12,400.0–13,400.0	14.7–72.8
Agriculture	1.8–7.9	4.4	–	0.6–139.8
Reduction fishery	–	69.8–8622.5	–	0.2–8.3
Farm	30.0–462.0	–	–	3.3–513.2
Farm for milk	–	–	–	17.8–107.2
Insects and worms	–	–	–	0.1–21.7
Fishery	2.2–23.9	–	–	2.7–72.8
Aquaculture	–	141.9	–	1.0–37.8
Algal aquaculture	–	–	–	−31.1–624.0
Metallurgic	–	–	7.9–12.8	–

Figure 9 depicts the climate change impact values range for the eight identified pigments. The operational factors which dictate the environmental impacts of the autotrophic microalgae production such as electricity and cultivation nutrients were discussed above. Additional impacts of this process are generally related to the extraction of the pigments from the biomass itself, i.e., use of ultrasounds or other mechanical pretreatment processes to break the cellular wall and permit the removal of the components. Furthermore, this stage should be followed by a liquid extraction with a polar solvent such as water, ethanol or buffer to separate the pigments from the cellular material prior to any additional purification stage. Some authors suggest that microalgal biomass should be dried prior to pretreatment and extraction phases. According to Papadaki et al. the use of a drying stage prior to the addition of solvent might increase the energy intensity of the process (unless if adopting the use of a non-energy dependent drying process such as solar drying) but allows for the more efficient incorporation of the solvent into the biomass, leading to higher pigment recovery yields in comparison with the use of the wet biomass [65]. Additionally, it also serves to reduce the risk of biomass contamination. Therefore, on top of the environmental impacts generally associated with microalgae production, there is an increase of energy expenditure and solvent usage related to the removal of the produced pigments. This factor contributes greatly to the higher range of climate change values represented in Table 3. As this product is generally for human consumption (food pigment, antioxidant compounds, cosmetics), the usual measures to improve environmental performance, such as the use of industrial waste streams and byproducts as well as wastewaters, cannot be employed. In this case, the most common approach to minimize this issue is the process design itself, i.e., the adoption of a biorefinery approach which considers the production of various commonalities instead of just one product. Furthermore, the electricity impact can be reduced with the introduction of a renewable electricity mix (at a supplier level) or the addition of a renewable electricity production system (such as solar panels, for example) associated to the facility as well as the use of solar oven for renewable biomass drying step if required. Some authors suggest that the recycling of water recovered during harvest should be undertaken as much as possible to reduce potable water consumption [65].

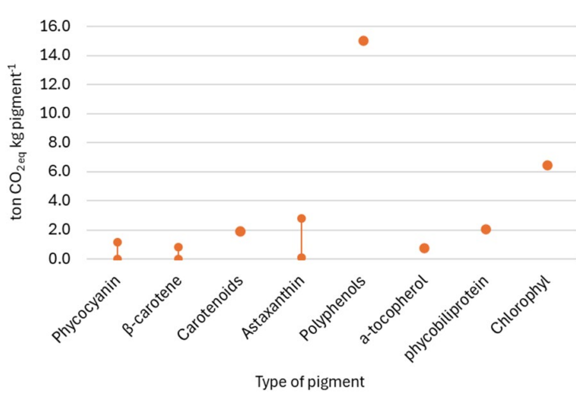

Fig. 9 Visual representation of the variation of published climate change impact values for the eight identified pigments

- PUFAs

  The analysis of the environmental data related to PUFA production was hampered by nomenclature issues. As specified in the materials and methods section, the query considered variations on the word *omega-*, encapsulating the various omega-3 and -6 desired for the nutritional market, and *PUFA*. A less stringent set of conditions led to the identification of a parallel body of work which consistently uses the nomenclature *DHA* and *EPA* instead of the more generic terminology. These works were disregarded during the analysis. The agro-industrial sector is the least representative when it comes to PUFA production. Agriculture and aquaculture were represented by a single study each and, as previously stated, disregarded from the analysis due to the lack of reproducibility. Reduction fishery, the term used to describe the valorization of wastes from the fishery industry (viscera, skins, bones), contributes significantly to PUFA production. As denoted in the previous section when referring to the use of wastes as feedstock, the more recalcitrant or complex nature of these materials requires the application of energy-intensive processes or the use of appropriate solvents. In the particular case of the extraction of omega-3, stages of degumming, washing and bleaching all contribute significantly to the climate change value [66] and the particular characteristics of the feedstock lead the high variability denoted in the quantified values. According to the data recovered by this study, PUFA is essentially produced through heterotrophic cultivation. This system is characterized by high productivity values, biomass concentrations and production scales. Its technology and engineering issues have been well established since the 70's with minor improvements. Unlike autotrophic production, cultivation is generally undertaken in closed bioreactors with the use of simple sugars as carbon source, resulting in more controlled ecosystems and predictable results. Glucose is generally preferred, as it can be assimilated by most microalgae with relatively high yields but its purified form, which is preferred for this type of production, has its own associated environmental burden [47]. A way of minimizing the impact of the carbon source in the production is the replacement of glucose or its equivalent with a sugar-rich residual waste or byproduct from another industry. However, as PUFA is intended for human consumption, the use of wastes as nutrient and carbon sources is restricted unless validated by the proper authorities. Additional environmental impacts are introduced into the system due to the energy expenditure required for the maintenance of fermentative conditions, particularly sterilization, temperature and stirring. Therefore, it was expected to have highly variable environmental impact results according to feedstock, electricity mix usage and allocation method (Table 3). Data related to the environmental impacts of this type of production was not very variable when compared to studies focused on other technologies, averaging a value of approximately 125 kg CO_2 per kg of PUFA. Variations to this value are either due to the allocation method used [67] or low TRL of the system under analysis, which required simulation with basis on bench-scale results and measurements [68]. Unlike previous technologies, however, the results obtained by microalgal cultivation consistently showed a better and stabler environmental performance.

- Lipids
  Studies focused on lipid production considered agriculture (oleaginous species), farm (livestock production), fishery (fish oil) and autotrophic microalgae as principal venues for production. A single entry (see Table 3) was registered through heterotrophic microalgae production and, as such, removed from the analysis due to lack of reproducibility. GWP values varied substantially according to the preferred use of the produced lipids, i.e., values of climate change impacts associated with lipids for human consumption were generally higher than for animal consumption. While the fractions both for food and feed undergo similar stages of production (such as cultivation, harvesting, processing, and transportation), the higher standards of quality associated to human consumption lead to more complex processing, logistics and higher energy-expenditures. Additionally, lipidic fractions for animal consumption are generally produced as a secondary stream, often with less quality or purity, resulting in studies which allocate most of the environmental impacts to the main products of the process.

The impact values from lipid fraction production can be divided clearly into two subsections: agro-industry-based and microalgae-based. The former encompasses all production methodologies from farm, agriculture and fishery and is characterized by being well-established, both economically and culturally, functioning under large-scale production systems and subjected to intensive optimization and with clearly defined uses, byproducts and waste valorization methods [69]. While the crop/culture productivity seems to be lower, (example: agriculture *vs.* microalgae production) [70], the associated yields, overall production value and percentage of product recovery are generally higher [71]. Traditionally, lipids from these venues are commercialized as food/feed products or as feedstock for biodiesel production or both in conjunction, i.e., the lipidic fraction is a byproduct of the food and feed process and then valorized through another pathway (example: animal fat wastes for biodiesel production). Oil production from agriculture can be obtained from specialized oil-rich crops such as rapeseed or soybean. In this type of crops, the production of oil cannot be undertaken without the co-production of a *meal* or another byproduct, generally rich in either protein, carbohydrates or both. According to Cavallet, the meal-to-oil ratio in soy can be as high as 4.5 [72]. Even accounting for the impacts of crop production (water use, fertilizer and electricity being the greatest contributors), the application of mass allocation to the LCA results leads to relatively low environmental impacts per kg of oil (at least when taking the climate change category into consideration). There was a relatively low number of results associated with oil from the livestock or fishing industries. This effect might be a consequence of the adopted query, i.e., a more careful analysis of publications on this subject showed that the authors generally employed the word *fat* instead of *lipids* or *oil*. This fact limited the number of generated results. As observed in the agricultural field, the lipidic fraction from the livestock industry is generally co-produced (example: protein corrected milk and fat) and the quantified environmental impacts are mass-allocated between the various products. However, unlike the agricultural industry, the main use of this fraction is for human consumption, requiring a higher level of processing and quality standards when compared to feed production. These additional stages of processing lead to an approximate ten-fold increase in quantified environmental impacts. Fish oil can be extracted directly from specific species of fish, reducing the expensive and extensive processing stages associated with the previous industries. It can also be obtained from byproducts/wastes of associated industries (such as fish canning), but the system tends to require higher levels of processing for the obtention of a marketable product with considerably lower final quality [73]. The climate change values for both industries were not significantly different except in two entries, obtained from the same study. Basto Silva et al. considered the use of poultry fat and fishing byproducts for the production of fat for feed and, in both cases, the values were approximately of an order of magnitude higher than the remaining entries [73]. This disparity is addressed in the study itself where it underlines that the assessment method did not consider the impact of industrial waste valorization and, consequently, the elimination of the associated disposal procedure.

The majority of lipid production identified in literature was associated with autotrophic microalgae cultivation. The environmental impact values from this type of production are typically high, resulting from the functioning of emerging technologies with lower technology readiness level (TRL), high initial investment costs and yet to be well-established. According to Thielemann et al. the analysis of the environmental impacts of autotrophic production must account for all the particularities of microalgal production, harvesting and processing [74]. Microalgae biomass growth, while often associated to atmospheric carbon capture, requires considerable quantities of electricity, nitrogen source and other essential elements such as, for example, vitamins or metal-based cofactors which are essential for cellular development. Additionally, compounds required for ecosystem simulation in the specific case of marine microalgae (e.g., sodium chloride) are also associated to high environmental impacts, especially in categories such as freshwater ecotoxicity and water use [2]. The harvesting stage is particularly energy-dependent, as autotrophic production is well known for low biomass concentrations at the harvest point, requiring particularly stringent centrifugation systems, membrane module systems or both working consecutively. This problem can be circumvented with the use of alternative technologies with a lower energy-dependency such as, for example, flocculation and electrocoagulation or adopting more modern filtration systems, already available at a commercial level. The processing stage can include cellular rupture systems, with or without drying and in the case of oil recovery, the requirement of the use of polar solvents is nearly obligatory for the separation of the product from the culture broth and cellular remains [75]. The majority of microalgal oil tends to be considered either for biodiesel production [11] or for human consumption due to its particular biochemical properties. As the former was not assessed in this study, the data available for microalgal production almost exclusively deals with the production of oils or lipid fractions for human consumption or its co-production with feed. The main usage of the produced material deals with human health and must follow stringent quality patterns to avoid potential damage to the consumer. Therefore, microalgal processing stages are more critical, requiring additional stages for the removal of contaminants, and the common venues for the decrease of environmental impacts such as wastewater usage or side streams from other industries are invalid. As a direct consequence, the climate change values quantified for this type of production were generally higher than those obtained from the agro-industrial sector. The exceptions to this observation generally consider the permanent capture of the CO_2 assimilated during the microalgal cultivation [76] or the use of residual streams (wastewater or another type of residue) as source of nutrients for cultivation [77].

- Proteins

  The body of work related to protein is the most extensive registered in this study, comprising 75% of the total of environmental-focused articles identified. There is a drive, particularly in the last years, not only to increase the amount of protein products developed worldwide (due to the worldwide increase of population and the lack of adequate protein intake per individual) but also of its quality and the environmental performance of its production [78]. Much has been stated in scientific circles and otherwise over the environmental burden of animal protein production (whether meat or other protein-rich products such as milk, cheese, or derivates) but its replacement with friendlier technologies associated with atmospheric carbon capture (plants, algae or microalgae) is still under assessment. The following data were categorized according to intended use: feed, food and feed and food, with the additional inclusion of the category "supplements" when appropriate.

  As observed in the previous sections, the intended use of the produced material influences greatly the attained results. Environmental impacts were more pronounced when the product was considered for human consumption, be it food or supplements. Products in this category are often subject to strict quality and purity requirements, meaning their production systems typically require more extensive processing and higher input use. This fact leads to distinctively higher values of climate change. However, it is important to discuss this data carefully as the numbers of entries for this category were particularly poor (less than 3 papers). These values should be seen as indicatory and not as absolute data. Production for human consumption (food) generated the highest values of climate change for all categories except microalgal production, where the category *food and feed* reached a maximum value approximately 100 times higher than those registered for *food*. A more in-depth analysis of the articles pertaining to this category revealed that the majority of this data were obtained through simulation based on literature data [79] or on bench-scale production data [80], which might overestimate environmental impacts. Additionally, the production of more than one stream of products will require the introduction of extra processing stages, increasing associated input requirements. In evaluating protein production methods, LCA studies show that farm-based protein production for food has the highest climate change impact, followed by protein production for milk and agricultural protein sources. The principal contributors for it being ruminant production (such as lignocellulosic material in the digestive track of ruminant animals) and the grassland or feed production [52, 81]. The latter is also the contributing factor to the environmental impact associated with other types of animal protein production such as chicken [82]. Common venues for improvement of the environmental results related to the enteric emissions suggest the addition of lipidic supplements to the livestock feed [83] or increasing starch concentration by the incorporation of grain into the cattle diet [84]. Copley and Wiedemann [85] suggest the use of locally produced grains as alternative feed to the more commonly used wheat or soybean meal [85]. As seen in Fig. 10, the production of protein from agriculture and fishery achieved the second and third highest values of identified climate change in this study, respectively. On average, the registered values represent an almost fourfold decrease when compared to protein obtained from farm production. Unlike the farm sector, the principal impact contributors were associated with energy expenditure, such as the electricity and diesel required for shipping and irrigation, transport of seeds and agricultural machinery [86]. Furthermore, it is also

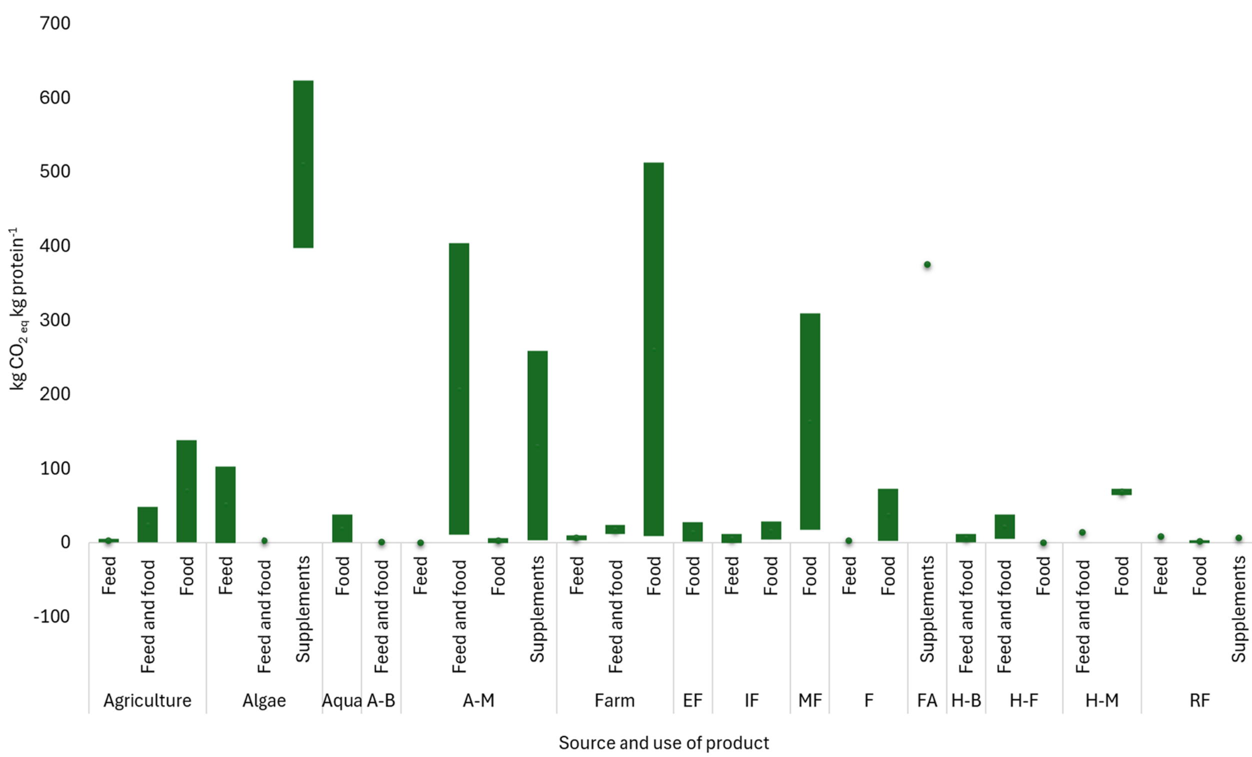

Fig. 10 Visual representation of the variation of published climate change values for protein production according to type of cultivation (Agriculture; Algae–macroalgae aquaculture; Aqua–fish aquaculture; A-B–autotrophic bacteria; A-M–autotrophic microalgae; Farm; EF–farm for eggs; IF–farm for insects; MF–farm for milk; F–fishery; FA–fishery for algae; H-B–heterotrophic bacteria; H-F–heterotrophic fungi; H-M–heterotrophic microalgae; RF–reduction fishery) and use (feed, feed and food, food)

necessary to account for the contribution associated to the use of the required synthetic fertilizers for soil enrichment [87] or the additional sources of impact which might be associated to the specific cultivated crop. For example, rice production in irrigated fields is associated with the production of relatively high levels of methane [88]. In this sector, methods for climate change mitigation vary greatly according to the cultivated crops and characteristics of cultivation, but authors seem to agree that the use of organic fertilizers, adoption of crop rotations and optimization of irrigation methodologies are appropriate forms to lessen environmental issues. Fish production can be divided neatly into fishery (wild-catch production) and aquaculture (large-scale fish farming). While the product itself is often of the same type and quality, the sources of environmental impact are significantly different. The main climate change contributor for fishery is fuel (diesel), used directly for boat/shipping operations (including fish processing and freezing), and the inputs necessary for boat maintenance, particularly the elimination of marine biofouling [89]. Svanes et al. quantified a total of 86% of the total GWP value exclusively generated from the fuel necessary for all the activities related to boat operation [90]. While in the previous sectors, climate change values could be improved with the introduction of renewable sources or operational optimizations, the improvement in this sector cannot depend on short term measures, instead relying on improvement of technological performance such as, for example, the improvement of engine efficiency. The simplest measure would be to reduce the distance of fishing activity in relation to the harbors, but such is often not possible due to water currents and animal behavior. Conversely, the major issue related to the environmental performance of aquaculture is the feed itself. Pelletier et al. developed a study focused on four countries (Norway, Canada, UK and Chile) and found that the environmental impact of the feed necessary for growth accounted for approximately 93% of the total climate change value of fish farming [91]. In a manner similar to the farming sector optimization, improvement of the environmental performance in the aquaculture sector has focused on the introduction of appropriate feed and feeding practices (such as appropriate ration and stock management and feed distribution) [92]. Additionally, results from aquaculture studies need to be cautiously approached since the boundaries of the studies may vary to include additional processing into canned goods or frozen food, which will include additional contributions (food oil usage, tin, freezing liquid) [93].

Limitations of the study

Various limitations in the research methodology were identified during data analysis. The data was gathered from a literature review conducted using the Web of Science™ database, which may introduce selection bias by excluding non-indexed sources, such as thesis, patents, or studies published in languages other than English. Lab-scale results were intentionally excluded whenever possible as (i) these data are notoriously unreliable when compared to large-scale facilities (above and including demo scale) and (ii) the benchmark aimed to analyze commercially available production systems with relatively high TRLs. This approach excludes potentially new technologies and advancements that could offer better environmental or techno-economic performance. Finally, nomenclature standardization was lacking across the entirety of the analyzed studies, which interfered with the query results for 3 out of 4 analyzed fractions and affected the quality and quantity of available datasets.

The principal limitation to the data analysis relates to unit standardization. The introduction of various sectors of activity leads to a vast number of products and potential functional units. As the interest of this study relates to the obtention of a fraction rich in each compound, the data from the various studies was translated into the functional unit of interest (example: kg of beef converted into kg of protein) when the required information was available in the text of the article. This approach does not account for the disparity in the chemical composition of the various materials, such as, for example, variation in the types of available proteins or PUFAs which can be obtained from the various sources. Therefore, this study assumes that the different fractions possess equivalent chemical and bioactive properties, allowing them to serve the same purpose. Generalization across diverse production systems presents another challenge. The study synthesizes data from diverse production systems, including autotrophic and heterotrophic microalgae, traditional agriculture, and aquaculture. While this provides a broad perspective, it also introduces complexity in generalizing findings across such varied systems. Specific contextual factors and operational nuances of each system might not be fully captured, especially when coordinated with different environmental impact allocation and calculation methods. Concluding this section, the environmental analysis performed in this study focused on climate change values, due to the greater amount of available information and its importance to the global climate change context. This fact does not remove importance to the other environmental impact categories, such as eutrophication, terrestrial and freshwater ecotoxicity, etc. These should be targeted in future study. Technological and economic variability also limited the findings in this study. Economic assessments were based on current market conditions and pricing, which are subject to change due to factors such as market demand, policy changes, and technological advancements. These dynamic market conditions can affect the long-term economic viability of the assessed production methods. Furthermore, regional differences in economic and environmental conditions were not considered, which could influence the applicability of the results in different geographical contexts.

Conclusions and future perspectives

The main objective of this study was to benchmark the available economic and environmental data related to the production of four key fractions, all of which can be obtained from microalgae biorefinery systems. Unlike various industrial sectors, the microalgae sector uniquely offers flexibility, allowing for the cultivation of different species, configurations and operational settings to produce each of these fractions. The introduction of a biorefinery approach enables multiple fractions to be produced within the same system, enhancing resource efficiency compared to traditional single-product models seen in other industries. Microalgae also serve as a prevalent source for pigment production across the studied sectors. However, environmental comparisons reveal that microalgal production often has the highest impact values due to its relatively low TRL, which faces bottlenecks in operational conditions, harvesting and processing stages. Although data gaps exist and further studies are needed to reduce the carbon footprint, optimization opportunities through the integration of industrial residues and wastewater are promising.

From a techno-economic perspective, the high CAPEX and OPEX associated with microalgae biorefineries—particularly for high-value products like pigments and PUFAs—are balanced by premium pricing in specialized markets such as pharmaceuticals and nutraceuticals. Studies demonstrated that, despite high production costs, microalgae-based pigments such as astaxanthin and phycocyanin remain economically viable, driven by market demand for purity and efficacy. Additionally, scaling up production shows a trend towards lower per-unit CAPEX, suggesting that economies of scale could further enhance profitability. For protein and lipid production, the complexity and capital demands of microalgae systems present challenges, though they also offer unique advantages in sustainability, particularly using non-arable land and non-potable water.

This study should not claim that a production process is better or worse in terms of environmental sustainability, as production methods and process stages significantly influence overall sustainability. Furthermore, the availability and quality of data vary across categories or fractions, making environmental assessments for emerging technologies, like microalgae biorefineries, less consistent. However, the established agro-industrial sectors show opportunities for improvement through modernization and optimization. As the field matures, microalgae biorefineries can support expanding markets and provide sustainable alternatives to traditional production, fulfilling niche needs without aiming to replace existing sectors entirely.

In conclusion, while microalgae biorefineries present a promising avenue for sustainable production, they face significant challenges in terms of environmental and economic impacts. Future research should focus on optimizing these systems and integrating them with existing industrial processes to maximize their potential. Moreover, government policies play a crucial role in adapting to technological advancements and innovation. Policymakers must develop frameworks that encourage research and development, provide financial incentives for sustainable practices and establish regulations that support the commercialization of innovative technologies. By fostering a supportive environment, governments can help facilitate the transition to more sustainable production methods and promote the widespread adoption of cutting-edge technologies in various sectors.

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Author contributions
Flávio Ferreira: Data collection and curation, Formal analysis, Writing—Original draft; Joana Ortigueira: Conceptualization, Methodology, Formal Analysis, Data Curation, Writing—Review and Editing, Supervision; Alberto Reis: Project Administration; Funding Acquisition; Writing—Review and Editing; Tiago F. Lopes: Conceptualization, Methodology, Writing—Review and Editing, Supervision.

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Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
Not applicable.

Competing interests
The authors declare no competing interests.

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