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Organic spirulina as a sustainable superfood: a tripartite sustainability assessment of an Italian production case study

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Introduction: Organic spirulina has emerged as a popular superfood, increasingly valued by consumers seeking foods that reduce the risk of non-communicable diseases and promote health and wellbeing. In this context, our study aimed to provide comprehensive tripartite sustainability assessment of spirulina production within an Italian agri-food business, considering environmental, social, and economic dimensions.

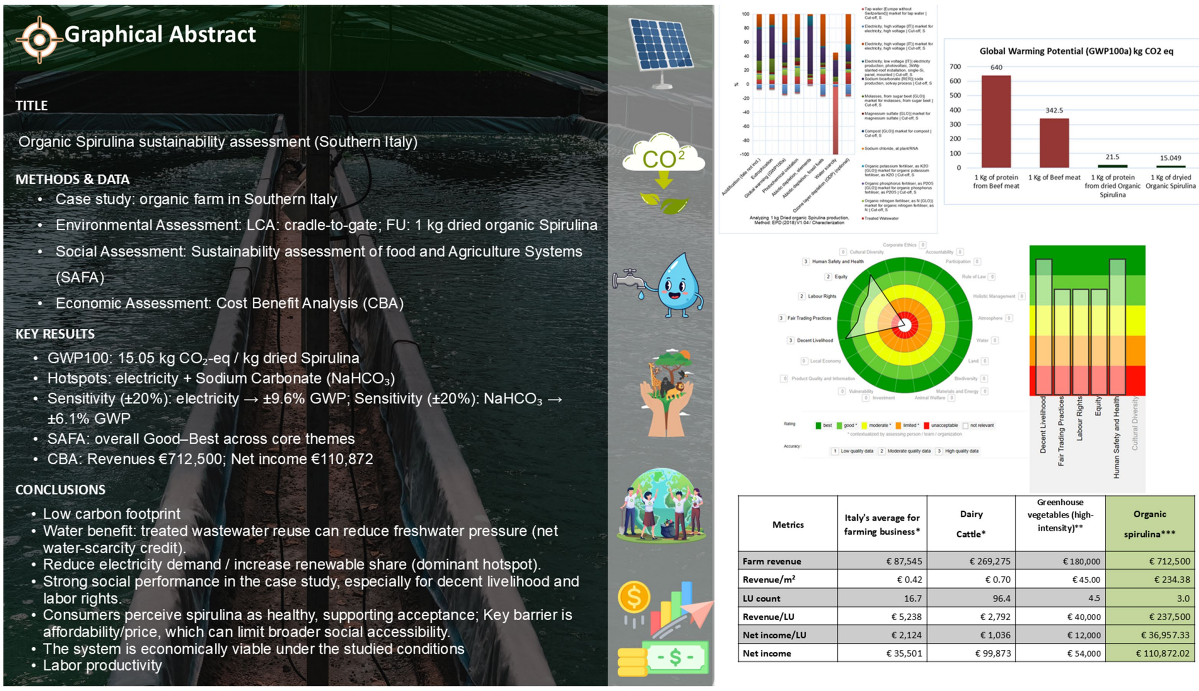
Methods: Three complementary methodologies were applied to evaluate sustainability performance. The environmental impact was assessed using a Life Cycle Assessment (LCA) with a functional unit of 1 kg of dried organic spirulina. Social wellbeing was analyzed through the SAFA tool, where the organic spirulina enterprise outperformed conventional spirulina production systems against social benchmarks in the Italian/Apulian context. Finally, economic performance was examined using Cost–Benefit Analysis (CBA).

Results: The LCA revealed a Global Warming Potential of approximately 15 kg CO_2 eq per kilogram of dried organic Spirulina. Social assessment results showed excellent performance (80–100%) in the themes of decent livelihood and human safety and health, and good performance (60–80%) in fair trading practices, labor rights, and equity, outperforming conventional Spirulina production. The economic evaluation demonstrated that revenues (€712,500), gross margin (€332,993), and net income (€110,872) significantly exceeded Italian farm averages.

Discussion: Overall, the findings highlight organic spirulina as a model of sustainable production within the circular economy, combining environmental responsibility, social wellbeing, and economic viability. This case study provides actionable insights for sustainable functional food innovation in Mediterranean contexts.

KEYWORDS

circular bioeconomy, Cost–Benefit Analysis, Life Cycle Assessment, organic microalgae, SAFA, sustainable protein



Graphical Abstract

TITLE

Organic Spirulina sustainability assessment (Southern Italy)

METHODS & DATA

- Case study: organic farm in Southern Italy
- Environmental Assessment: LCA: cradle-to-gate; FU: 1 kg dried organic Spirulina
- Social Assessment: Sustainability assessment of food and Agriculture Systems (SAFA)
- Economic Assessment: Cost Benefit Analysis (CBA)

KEY RESULTS

- GWP100: 15.05 kg CO_2-eq / kg dried Spirulina
- Hotspots: electricity + Sodium Carbonate ($NaHCO_3$)
- Sensitivity (±20%): electricity → ±9.6% GWP; Sensitivity (±20%): $NaHCO_3$ → ±6.1% GWP
- SAFA: overall Good–Best across core themes
- CBA: Revenues €712,500; Net income €110,872

CONCLUSIONS

- Low carbon footprint
- Water benefit: treated wastewater reuse can reduce freshwater pressure (net water-scarcity credit).
- Reduce electricity demand / increase renewable share (dominant hotspot).
- Strong social performance in the case study, especially for decent livelihood and labor rights.
- Consumers perceive spirulina as healthy, supporting acceptance; Key barrier is affordability/price, which can limit broader social accessibility.
- The system is economically viable under the studied conditions
- Labor productivity

Metrics	Italy's average for farming business*	Dairy Cattle*	Greenhouse vegetables (high-intensity)**	Organic spirulina***
Farm revenue	€ 87,545	€ 269,275	€ 180,000	€ 712,500
Revenue/m²	€ 0.42	€ 0.70	€ 45.00	€ 234.38
LU count	16.7	96.4	4.5	3.0
Revenue/LU	€ 5,238	€ 2,792	€ 40,000	€ 237,500
Net income/LU	€ 2,124	€ 1,036	€ 12,000	€ 36,957.33
Net income	€ 35,501	€ 99,873	€ 54,000	€ 110,872.02

GRAPHICAL ABSTRACT

1 Introduction

Global food systems face converging pressures: feeding nearly 10 billion people by 2050 while meeting climate goals, protecting ecosystems, and ensuring equitable livelihoods (FAO, 2017). Consumers are increasingly interested in foods that reduce the risk of non-communicable diseases and promote wellbeing (Mohamad et al., 2014; Annunziata and Vecchio, 2016). Recent studies on innovative functional foods, such as ready-to-eat legume snacks, confirm that nutritional attributes and labeling claims strongly influence Italian citizens' willingness-to-pay (Petrontino et al., 2023a; D'Amico et al., 2024; Petrontino et al., 2024). Spirulina (*Arthrospira* spp.), a cyanobacterium recognized for its high protein content, essential micronutrients, and bioactive compounds, has emerged as a promising superfood and functional food ingredient (Ali and Saleh, 2012; Belay, 2013). Its cultivation requires less land and water than conventional protein sources, and it can be integrated into circular bioeconomy models, including wastewater recycling and carbon capture (Lipok et al., 2007; Cain et al., 2008; Sutherland and Ralph, 2019).

Globally, microalgae production reached 56,456 tonnes in 2019, with spirulina accounting for 56,208 tonnes across 10 reporting countries, dominated by China (FAO FishStatJ, 2024). The EU contributes only around 0.63% of global production, though policy frameworks such as the EU Algae Initiative are accelerating sector development (Gerhard et al., 2023). The sustainability of novel food systems like spirulina production requires holistic evaluation across environmental, social, and economic dimensions, a methodological challenge that has gained prominence in agri-food research (Hayati et al., 2011).

Life Cycle Assessments (LCA) have demonstrated spirulina's environmental advantages compared to animal proteins. For example, geothermal-powered photobioreactors in Iceland achieved near net-zero emissions and >99% GHG reductions compared to beef production (Quintero et al., 2021; Tzachor et al., 2022). French studies of open and closed raceway ponds highlighted electricity use and sodium bicarbonate inputs as major contributors to GWP, with seasonal open ponds achieving around 15.5 kg CO_2-eq/kg biomass (Quintero et al., 2021). Integrating carbon capture from breweries or direct air capture reduced spirulina's emissions by around 46–52% (Fernández-Ríos et al., 2023). Social sustainability, however, is less routinely integrated into such assessments, despite the availability of frameworks such as the FAO's Sustainability Assessment of Food and Agriculture (SAFA) guidelines, which have been used to evaluate themes like decent livelihood, fair trading, and labor rights in agri-food systems (Zahm et al., 2008; El Bilali et al., 2020). Economically, Cost–Benefit Analysis (CBA) offers a tool to assess viability, yet few studies combine LCA, SAFA, and CBA into a single, multi-dimensional assessment, a gap that limits the practical policy and business insights derived from sustainability science (De Olde et al., 2016; Mkindi et al., 2021).

Despite growing interest in spirulina as a sustainable protein source, three methodological gaps persist: (i) few integrated sustainability assessments simultaneously evaluate environmental, social, and economic dimensions for organic spirulina in real production settings; (ii) most LCAs focus on cultivation scenarios rather than factory-level 'cradle-to-gate' impacts of dried spirulina as a processed ingredient; (iii) social assessments using frameworks like SAFA remain limited for microalgae, particularly in certified-organic contexts (El Bilali et al., 2020; Fernández-Ríos et al., 2023); and (iv) benchmarking against national agri-food economics: Comparative analyses with Italian farm business averages (CREA, 2023) are scarce. As such, the originality and relevance of this research might be envisaged in conducting a tripartite sustainability assessment of organic spirulina production in Italy, aligning with EU circular bioeconomy goals and functional food innovation. Socio-economic risks in agri-food systems, such as those posed by plant diseases in the Mediterranean (Cardone et al., 2022), underline also the importance of integrating social and economic dimensions into sustainability assessments.

This study aims to address these gaps through a tripartite sustainability assessment of an organic spirulina production facility in Southern Italy, with the following specific objectives to: (i) quantify the cradle-to-gate environmental impacts of 1 kg dried organic spirulina via LCA; (ii) assess social wellbeing using the SAFA framework complemented by contextual consumer insights; (iii) evaluate economic viability through CBA, benchmarked against relevant Italian agricultural sectors; (v) compare organic spirulina's sustainability performance against conventional spirulina and animal protein systems; and (iv) provide integrated recommendations for sustainable processed food innovation. For these purposes, we adopt a case study design of an organic spirulina firm, in Southern Italy and, we used simultaneously the LCA (ISO 14040/44) with impact categories including GWP, acidification, eutrophication, and water scarcity for the environmental sustainability, the SAFA tool applied to themes of livelihood, equity, labor rights, and health, supplemented by consumer surveys for the social sustainability assessment, and the CBA including revenues, gross margin, net income, and labor productivity, benchmarked against CREA dataset for the economic sustainability assessment. Based on the literature, we hypothesize that:

> *H_1:* Organic spirulina production will demonstrate a lower carbon footprint per unit protein than conventional spirulina and substantially lower than beef protein.
>
> *H_2:* The enterprise will perform strongly on social indicators related to labor rights and fair trading due to its organic certification and circular economy model.
>
> *H_3:* Despite higher production costs, organic spirulina will show economic viability through premium pricing and efficient resource use, outperforming conventional farm averages in key productivity metrics.

2 Materials and methods

2.1 Case study

The case study focuses on an organic spirulina production facility in Southern Italy, operating under certified organic standards. The facility integrates circular economy principles through a closed-loop system in which wastewater from pasta-making processes is purified via an oxidation system and reverse osmosis and then reused as a nutrient source for spirulina cultivation. Water consumption is managed through 1,300 m^3/year sourced from treated pasta-process wastewater and 1,608 m^3/year supplied by Acquedotto Pugliese, totaling 2,908 m^3/year. The analyzed operating period corresponds to the facility's seasonal production window (April–November 2023) carried out on a total area of 3,040 m^2, using two raceway ponds under greenhouse cover (1,440 m^2 established in 2021 and 1,600 m^2 established in 2023). Harvesting occurs every 1–3 days depending on culture density, followed by rapid quality checks and drying in an oven, producing an annual yield of approximately 3 tons of dried spirulina (about 1.5 tons per greenhouse). From a process perspective, production follows a greenhouse-compatible microalgae configuration based on open raceway pond cultivation requiring continuous mixing and circulation, followed by downstream processing where drying is necessary to stabilize biomass for food use. Because mixing/circulation and drying are electricity-intensive, energy demand is both an environmental hotspot and a key operational consideration addressed explicitly in the environmental discussion and limitations. The life-cycle inventory reflects the facility's organic and circular inputs, including treated wastewater, organic fertilizers (NPK sources), and culture-management additives such as sodium bicarbonate, together with background datasets from Ecoinvent, and represents a pioneering model within the Italian agri-food sector. Case studies are widely used in sustainability research to provide context-specific insights into environmental, social, and economic performance (Binder et al., 2010; Campagnolo et al., 2018). By situating the analysis in a real-world factory, this study contributes practical evidence to the broader debate on sustainable food systems (FAO, 2017).

2.2 Data collection

Data collection combined both primary and secondary sources to ensure methodological robustness. Primary data were obtained from the factory records detailing inputs such as electricity, water, fertilizers, labor and packaging, as well as outputs including biomass yields. In addition, surveys and interviews were conducted with managers, workers, and consumers to evaluate social wellbeing and perceptions of organic spirulina. All the operational data correspond to April–November 2023 (seasonal operation). Secondary data were drawn from official databases (CREA, 2023; FAO FishStatJ, 2024), international standards, and peer-reviewed literature on spirulina production and sustainability (Belay, 2013). This triangulation of sources aligns with best practices in sustainability assessment, enhancing the reliability and validity of the study (Dantsis et al., 2010; De Olde et al., 2016).

2.3 Methodological framework

Three complementary methodologies were applied to evaluate sustainability performance: Life Cycle Assessment (LCA) for environmental impacts, SAFA tool and citizen survey for social wellbeing, and Cost–Benefit Analysis (CBA) for economic viability. This single tripartite assessment approach reflects the multidimensional nature of sustainability (Hayati et al., 2011). To ensure that environmental, social, and economic findings are interpreted through a cross-dimensional synthesis logic, we applied an integrative synthesis approach that explicitly identifies cross-dimensional synergies and trade-offs. Specifically, we interpret LCA hotspot drivers (e.g., electricity demand for drying and circulation) jointly with CBA cost drivers and with SAFA/survey insights on labor performance and consumer affordability, so that improvement options are evaluated for their combined sustainability consequences rather than within one pillar only. Similar integrated approaches combining environmental and economic assessments have been applied in nursery plant production under pest outbreaks (Frem et al., 2022), in table grape production (Cardone et al., 2018), highlighting the value of coupling LCA with CBA for agri-food sustainability.

2.3.1 Environmental sustainability assessment: LCA

The environmental impact of organic spirulina production was assessed using LCA, conducted in accordance with ISO 14040 and ISO 14044 standards. The study adopted a cradle-to-gate perspective with a functional unit defined as 1 kg of dried spirulina biomass [consistent with previous sustainability assessments of microalgae (Quintero et al., 2021; Tzachor et al., 2022)]. System boundaries encompassed cultivation, harvesting, drying, packaging, and energy inputs Figure 1, while the Life Cycle Inventory (LCI) incorporated electricity, water, fertilizers (organic nitrogen and phosphorus), sodium bicarbonate, and packaging materials. Environmental impacts were evaluated using the EPD (2018) V1.04 method, which provides characterization factors across multiple categories, including Global Warming Potential (GWP), acidification, eutrophication, photochemical oxidation, water scarcity, and ozone depletion. Importantly, abiotic depletion was assessed in two distinct categories, mineral/metal depletion and fossil fuel depletion, with the latter often representing a major contributor to overall environmental burdens. This approach reflects established frameworks for protein foot printing and sustainable diet assessments (Parodi et al., 2018). This approach builds on prior LCAs of spirulina cultivation, which identified energy use and bicarbonate inputs as major contributors to environmental burdens (Cuellar-Bermudez et al., 2015; Fernández-Ríos et al., 2023).

Electricity use was modeled using foreground consumption data from the case-study facility and background datasets from Ecoinvent, reflecting a mixed supply between grid electricity and on-site photovoltaic generation. In the life cycle inventory per functional unit, electricity inputs include 18.1686 kWh from "market for electricity, high voltage, IT" and 6.056 kWh from "electricity production, photovoltaic, 3 kWp slanted-roof installation, IT," consistent with the reported around 75/25 grid-to-PV split. These explicit datasets and quantities are provided to enable full replication of the electricity hotspot identified in the Life Cycle Impact Assessment (LCIA) contribution analysis.

To assess the robustness of the LCIA results to plausible uncertainty in key foreground inventory parameters, we performed a deterministic one-way sensitivity analysis (Supplementary material A). Selected parameters were varied individually by ±20% around their baseline values (grid electricity, photovoltaic electricity/avoided grid electricity, sodium bicarbonate, treated wastewater/avoided tap water, organic fertilizers, molasses, compost, and minor salts), while all other inputs were held constant. The change in each impact category was approximated by linearly scaling the baseline contribution of the corresponding input/process in the LCIA contribution analysis, which provides a first-order screening of result sensitivity when full parameter distributions are not available. This one-way analysis complements the deterministic base-case results; a probabilistic Monte Carlo uncertainty analysis is recommended for future work once uncertainty distributions can be parameterized for all foreground inputs.

2.3.2 Social wellbeing sustainability assessment: SAFA tool and citizen survey

Social wellbeing was evaluated using the SAFA framework developed which provides a comprehensive tool for assessing sustainability in food and agriculture systems. The analysis focused on key themes including decent livelihood, fair trading practices, labor rights, equity, and human safety and health, with indicators such as wage level, employment relations, non-discrimination, gender equality, workplace safety, health

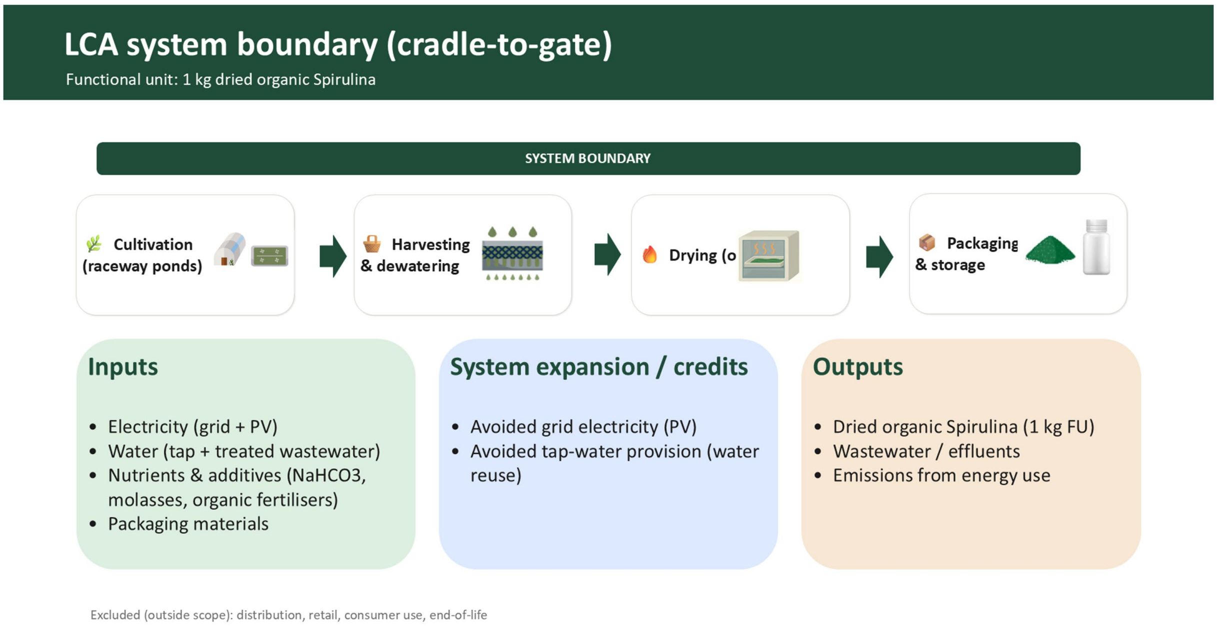


FIGURE 1
LCA system boundary (cradle-to-gate) for dried organic spirulina (functional unit: 1 kg dried organic spirulina).

TABLE 1 SAFA social wellbeing indicators.

Theme	Sub-themes	Default indicators
S1 Decent livelihood	S 1.1 Quality of life	S1.1.1 Right to quality of life
		S 1.1.2 Wage level
	S 1.2 Capacity Development	S 1.2 Capacity development
	1.3 Fair Access to Means of Production	S 1.3.1 Fair access to means of production
S2 Fair trading practices	S 2.1 Responsible buyers	S 2.1 Responsible buyers
	S 2.1.1 Fair pricing and transparent contracts	S 2.1.1 Fair pricing and transparent contracts
S3 Labor rights	S 3.1 Employment relations	S 3.1.1 Employment relations
	S 3.2 Forced labor	S 3.2.1 Forced labor
	S 3.3 Child labor	S 3.3.1 Child labor
S4 Equity	S 4.1 Non-discrimination	S 4.1.1 Non-discrimination
	S 4.2 Gender equality	S 4.2.1 Gender equality
S5 Human safety and health	S 5.1 Workplace safety and health provisions	S 5.1.1 Safety and health training
		S 5.1.2 Safety of workplace, operations and facilities
		S 5.1.3 Health coverage and access to medical care
	S 5.2 Public Health	S 5.2 Public health

Source: FAO (2014).

TABLE 2 Category of performances associated with colors and percentage scores.

Performance	Color	Score (in %)
Best	Dark green	80–100
Good	Light green	60–80
Moderate	Yellow	40–60
Limited	Orange	20–40
Unacceptable	Red	0–20

Source: FAO (2014).

coverage, and public health. These indicators, rearranged in Table 1, were assessed through semi-structured interviews and questionnaires targeting various stakeholders within the concerned firm to ensure comprehensive coverage of relevant data needed to evaluate the social wellbeing dimension. Through voluntary assessments, the rating system for the selected indicators assigns each value a color for easy interpretation. The performance categories are rearranged in Table 2.

To complement the SAFA assessment with contextual market and consumer insights, a small-scale, exploratory survey was conducted among citizens in the local area where the spirulina is consumed. The survey was not intended for statistical generalization but to capture qualitative perceptions within a niche market. Given the niche, localized nature of this organic spirulina enterprise and the study's design as an in-depth single case study, a purposive sample of 38 participants was collected. This sample size is aligned with established qualitative research methodologies for achieving thematic saturation in bounded, context-specific investigations, where the goal is depth of understanding rather than breadth of representation (Yin, 2018). Participants included both spirulina consumers and non-consumers familiar with the product. The survey explored themes of product awareness, perceived affordability, health motivations, and cultural perceptions (Petrontino et al., 2022) using a mix of closed and open-ended questions. All quantitative data from closed questions are presented descriptively with absolute numbers and percentages to ensure transparency (Table 3) and are interpreted alongside qualitative insights from open responses.

This triangulated approach, combining SAFA (producer practices), survey insights (local citizen perceptions), and open-ended feedback, provides a richer, more nuanced understanding of social sustainability within this specific case study context, consistent with best practices for embedded social research in agri-food systems (El Bilali et al., 2020; De Boni et al., 2022).

2.3.3 Economic sustainability assessment: CBA

Economic performance was assessed using CBA, a well-established tool in agricultural economics for evaluating farm viability and profitability (Mkindi et al., 2021). The analysis considered key financial indicators, including fixed costs, variable costs, total costs, revenues, gross margin (GM), and net income (NI), alongside labor-related metrics such as labor days, labor units (LU), labor income, revenue per labor hour, and GM per labor hour. The CBA is implemented as a single-period operating-year accounting assessment (operating year), aligned with the production season reported in the case dataset (April–November) and presented using annual totals for costs and revenues using annual totals for revenues and for variable and fixed costs consistent with farm-budget style indicators (gross margin, net income, and related ratios).

Fixed assets are annualized using straight-line depreciation based on reported initial values, residual values, and useful lives, defining the time basis of the fixed-cost component. To address sensitivity to energy prices, we added a deterministic electricity-price sensitivity using the recorded process electricity consumption (mixing/aeration 15,574 kWh; lab/lighting 3,892 + 3,892 kWh; drying 31,148 kWh; pumping/treatment 23,360 kWh) and the baseline tariff assumption (€0.20/kWh). Total electricity demand is therefore 77,866 kWh/year, corresponding to around €15,573/year in electricity costs in the base case, and we report sensitivity scenarios at €0.15/kWh and €0.30/kWh to reflect plausible tariff variation. Under these scenarios, holding all else constant, net income would increase by around €3,893 at €0.15/kWh and decrease by around €7,787 at €0.30/kWh relative to the baseline net income reported for the case To contextualize the results, the outcomes of organic spirulina production were benchmarked against multiple reference points using official datasets from CREA (2023): (i) the national average for Italian farms, providing context within the broader agricultural sector; (ii) the dairy cattle sector as a representative high-value livestock system; and (iii) greenhouse

TABLE 3 Consolidated citizen survey results on organic spirulina.

Category	Sub-category	Number of participants (*N*)	Percentage (%)
Demographics	Age 18–39	35	92
	Age 40–60	3	8
Awareness & knowledge	Aware of spirulina	34	89
	Not aware	3	8
	Comprehensive knowledge	17	45
	Basic/Moderate awareness	17	45
Affordability perception	Expensive	15	39
	Neutral	12	32
	Affordable	4	11
	Very Expensive	2	5
	Very Affordable	1	3
	I Do not Know	2	5
Health impact motivations	Nutritional/health value	22	58
	Novelty/trendy superfood	7	18
	Ease of diet integration	6	16
	Recommendation from healthcare professional	2	5
	Environmental sustainability/low impact	1	3
Cultural & social perception	Yes (respects local culture)	9	24
	Maybe	16	42
	No	11	29
	No answers	2	5

Percentages are calculated based on the total sample (*N* = 38) and may not sum to exactly 100% due to rounding.

vegetable production as a technologically advanced, controlled-environment cropping system more structurally comparable to intensive microalgae cultivation. This multi-tiered approach acknowledges the distinctive bioprocessing nature of spirulina production while situating its economic performance within relevant agricultural contexts.

In addition, this approach highlights spirulina's economic viability relative to conventional Italian farm businesses, consistent with findings that microalgae can outperform traditional crops in profitability under optimized conditions (Costa et al., 2019; Cardone et al., 2021a; Cardone et al., 2021b).

3 Results

3.1 LCA results

The LCA of organic spirulina production revealed a GWP of approximately 15 kg CO_2-eq per kilogram of dried biomass (Table 4). Other impact categories from the LCIA confirmed moderate environmental burdens: acidification at 0.10 kg SO_2-eq/kg, eutrophication at 0.03 kg PO_4^{3-}-eq/kg, photochemical oxidation at 0.05 kg NMVOC, abiotic depletion at 0. 0.0002 kg Sb-eq/kg, water scarcity at −22.19 m^{3}eq, and ozone depletion at 2.5828E−07 kg CFC-11-eq/kg. The largest contributor to GWP is electricity (high voltage grid supply) accounting for 7.21 kg CO_2 eq (approximately 47.97% of the total impact) (Figure 2), calculated using the standard Italian grid emission factor without renewable energy adjustments. Other notable contributors include sodium bicarbonate (4.56 kg CO_2 eq), treated wastewater (2.277 kg CO_2 eq), and organic nitrogen fertilizer (1.54 kg CO_2 eq), while molasses contribute 0.78 kg CO_2 eq. In contrast, emissions were avoided from the use of local tap water and electricity from the local grid, totaling −2.704 kg CO_2 eq. As such,

TABLE 4 Life cycle impact assessment results.

Impact category	Unit	Total
Acidification (fate not incl.)	kg SO_2 eq	0.105158457
Eutrophication	kg PO_4---eq	0.031097273
Global warming (GWP100a)	kg CO_2 eq	15.04916239
Photochemical oxidation	kg NMVOC	0.056862072
Abiotic depletion, elements	kg Sb eq	0.000209377
Abiotic depletion, fossil fuels	MJ	177.4424139
Water scarcity	m^3 eq	−22.19613112
Ozone layer depletion (ODP) (optional)	kg CFC-11 eq	2.5828E−07

these findings confirm Spirulina's potential as a climate-friendly protein source, with the negative water scarcity value indicating a significant water-saving advantage due to the use of treated wastewater. Furthermore, the baseline GWP is 15.05 kg CO_2-eq per kg of dried spirulina. Varying grid electricity use by ±20% changes the GWP to 13.61–16.49 kg CO_2-eq/kg (−9.6 to +9.6% relative to baseline), confirming electricity as the dominant robustness lever. Varying sodium bicarbonate by ±20% changes the GWP to 14.14–15.96 kg CO_2-eq/kg (−6.1 to +6.1%). Varying treated wastewater/avoided tap water by ±20% changes the GWP to 14.65–15.45 kg CO_2-eq/kg (−2.6 to +2.6%). Varying photovoltaic electricity/avoided grid electricity by ±20% changes the GWP to 15.43–14.67 kg CO_2-eq/kg (+2.5% to −2.5%), indicating that increasing the renewable share provides a consistent (though smaller) reduction in climate impacts under the current grid/PV split (Table 5).

3.2 SAFA results

The SAFA-based social sustainability assessment demonstrated "best performance" (80–100%) in "Decent Livelihood" and "Human Safety and Health," reflecting strong wage levels, workplace safety, and access to medical care. "Good performance" (60–80%) was observed in "Fair Trading Practices," while "Labour Rights" and "Equity" also achieved "Good" (60–80%), outperforming conventional spirulina production systems. "Cultural Diversity" was assessed as not relevant for this case study. These results, as visualized in Figures 3, 4, highlight the social sustainability of the firm, which ensures decent working conditions, fair wages, and responsible practices within its organizational model.

3.3 Citizen survey results

Table 3 consolidates all the survey results in terms of demographics, awareness, affordability, health motivations, and cultural perception. These findings are descriptive and indicative of themes within this specific case context, not statistically generalizable to broader populations. The majority of whom were between 18 and 39 years old (35 respondents), with only three participants aged 40–60, and their educational backgrounds ranged from high school diplomas to bachelor's, master's, and professional degrees. Awareness of spirulina was high, with 89% of respondents familiar with the product and 17 demonstrating comprehensive knowledge and suggesting strong market penetration. In terms of affordability, 39% of participants considered organic spirulina expensive, 32% viewed it neutrally, and 11% found it affordable, while smaller proportions rated it very expensive (5%), very affordable (3%), or were unsure (5%). As such, price remains a barrier, with nearly 40% perceiving spirulina as expensive. Health-related motivations were particularly strong, as 58% reported consuming spirulina for its nutritional and health value, with others citing novelty, ease of integration into their diet, or sustainability as reasons. As such, nutritional and health benefits are the main drivers of consumption. Finally, cultural and social perceptions revealed mixed views: 24% believed spirulina respects and preserves local culture, 42% were uncertain, and 29% did not perceive such a contribution, indicating potential for improved cultural integration strategies. These findings emphasize that while the firm demonstrates excellent social sustainability performance, the production and consumption of spirulina directly influence citizens' perceptions of wellbeing, highlighting the dual dimension of social sustainability: the enterprise's practices and the product's societal impact. As such, these insights suggest that within this local market context, awareness and health perceptions are strengths, while price remains a notable barrier for a substantial segment. The mixed cultural perceptions highlight an area for potential communication and product positioning strategies by the enterprise. The survey thus serves to contextualize the strong SAFA performance at the production level with the lived perceptions within the local consumer environment.

3.4 CBA results

The economic evaluation demonstrated clear advantages for organic spirulina production compared to average Italian farms. Annual revenues reached €712,500, far exceeding the Italian farm average of €87,545 and even dairy cattle farms at €269,275. The gross margin (GM) was €332,993.32, while net income (NI) amounted to €110,872.02, both substantially higher than the national averages of €35,501 for farming businesses and €99,873 for dairy cattle. These results are detailed in Tables 6**,** 7. Labor profitability metrics also confirmed Spirulina's efficiency: the enterprise reported 1,150 labor days per year, equivalent to 3 labor

TABLE 5 The top sensitivity levers for GWP (±20% one-way variation).

Lever	Baseline value	Unit	Contribution baseline	Total_ minus	Total_plus	Pct_minus (%)	Pct_plus (%)
Grid electricity (high voltage) kWh	18.169	kWh	7.218	13.61	16.49	−9.6	9.6
Sodium bicarbonate kg	5	kg	4.559	14.14	15.96	−6.1	6.1
Water (treated wastewater + avoided tap water) kg	969.33	kg	1.980	14.65	15.45	−2.6	2.6
PV electricity (low voltage) + avoided grid kWh	6.056	kWh	−1.904	15.43	14.67	2.5	−2.5
Organic N fertilizer kg	2.5	kg	1.537	14.74	15.36	−2.0	2.0

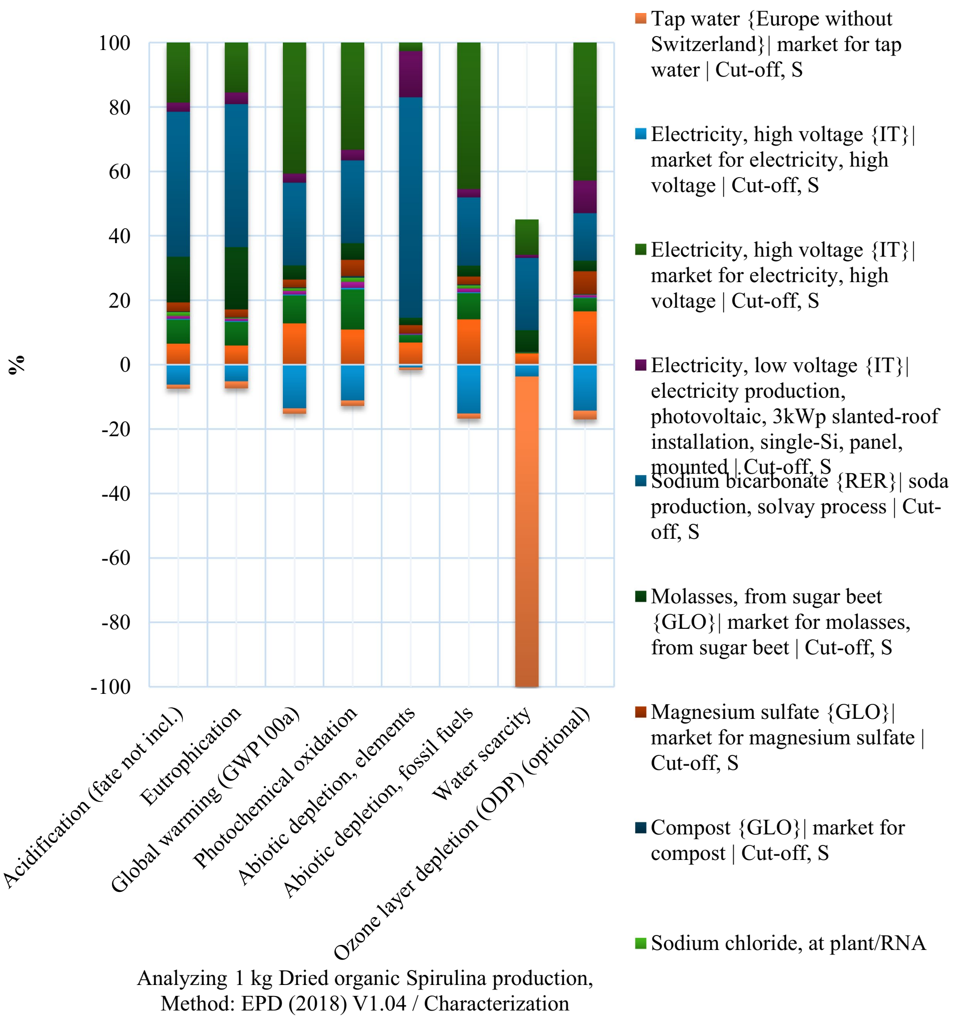


FIGURE 2
Input contribution across impact category (in %).

units (LU), with a labor income of €124,200/year. Productivity indicators showed revenue per labor hour at €103.26/h, compared to around €12/h for Italian farms, and GM per labor hour at €48.26/h, compared to around €8/h. As such, these results confirm spirulina's economic viability as a sustainable agri-food innovation. Higher revenues and margins reflect strong market demand and efficient resource use. Labor profitability metrics also exceeded benchmarks, suggesting spirulina can provide decent livelihoods while remaining competitive in the Italian agri-food sector.

4 Discussion

Our study uses triangulation (cross-validation in a qualitative sense) by combining multiple evidence streams: factory records and standardized LCA modeling for environmental performance, SAFA interviews/questionnaires plus a contextual consumer survey for social interpretation, and CBA using detailed financial indicators benchmarked against official CREA comparators. Regarding sensitivity, please refer to our answers above. The findings of this tripartite assessment allow us to evaluate the initial research hypotheses. H_1 is confirmed: organic spirulina production demonstrated a substantially lower carbon footprint (15 kg CO_2-eq/kg biomass) than conventional spirulina systems and, when expressed per unit of protein, a reduction exceeding 95% compared to beef protein, positioning it as a low-carbon alternative. H_2 is also supported: the SAFA assessment revealed "good" to "best" performance in social themes such as labor rights and fair trading, which can be attributed to the enterprise's organic certification and circular economy model, aligning with the expected positive social outcomes. Finally, H_3 is confirmed: despite higher production costs, the economic analysis demonstrated clear viability, with revenues (€712,500), gross margin (€332,993), and net income (€110,872) significantly exceeding Italian farm averages, and labor productivity metrics far outperforming conventional sectors, validating the model's economic resilience through premium pricing and efficient resource use.

4.1 Comparative environmental performance

In our case of the dried organic spirulina production compares GWP with other sources of protein which is beef production so the GWP for 1 kg of dried organic spirulina production is 15.049 kg

FIGURE 3
Social wellbeing results according to the SAFA sustainability polygon.

CO_2-eq. However, when considering protein content as the functional unit (FU), spirulina contains approximately 65–70% protein by dry weight. Using the higher estimate (70%), the GWP for 1 kg of Spirulina protein would be 21.5 kg CO_2-eq per kg protein, this value is significantly lower compared to the upper limit of 640 kg CO_2-eq per kg of protein and the average of 342.5 kg CO_2-eq per kg of protein for beef production. This suggests that organic spirulina production has a substantially lower carbon footprint when compared to traditional protein sources like beef as in Figure 5.

As shown in Table 8, the GWP of organic spirulina production (including processing impacts) is compared with results from Quintero et al. (2021), specifically with the seasonal cultivation Scenario 5 (ORP). This scenario is aligned with favorable seasons, avoiding winter production and eliminating the need for energy-intensive heating, leading to a low GWP of 15.5 kg CO_2-eq per kg biomass. Both the studied organic spirulina system and this seasonal ORP system exhibit very similar total GWP values (15.05 and 15.5 kg CO_2-eq/kg, respectively). Electricity and sodium bicarbonate are major contributors in both systems. In contrast, the standard year-round cultivation scenario has the highest GWP (28.2 kg CO_2-eq/kg), where thermal regulation and infrastructure significantly raise impacts compared to the organic case (15.05 kg CO_2-eq/kg).

Electricity use for drying and sodium bicarbonate inputs emerged as the main hotspots (48% of GWP), consistent with prior studies on microalgae cultivation (Cuellar-Bermudez et al., 2015; Fernández-Ríos et al., 2023). These findings align with prior studies emphasizing the need to optimize energy inputs and bicarbonate use to reduce environmental burdens (Cuellar-Bermudez et al., 2015; Fernández-Ríos et al., 2023). This dominance of electricity in GWP (48%) is mechanistically driven by energy-intensive unit processes specific to microalgae biorefining. Drying, required to stabilize biomass for food use, consumes significant thermal and/or electrical energy to remove water from a high-moisture slurry. Mixing and circulation in open raceway ponds, necessary to prevent sedimentation and ensure gas exchange, require continuous pumping. These processes contrast with conventional field crops where fertilization typically dominates impacts, highlighting different intervention points for sustainability improvement in algae systems. The negative water scarcity result (−22.20 m^3eq, Table 3) reflects the advantage of using treated wastewater, a significant benefit in water-stressed Mediterranean regions. In addition, integrating renewable energy (e.g., geothermal, solar) and carbon capture (brewery CO_2, direct air capture) could further reduce emissions, making spirulina a viable ingredient for sustainable processed foods. Similarly, the notable contribution of sodium bicarbonate (30% of GWP) stems from its role as the primary inorganic carbon source for photosynthesis in closed systems; its production via the Solvay process is energy- and emissions-intensive. This highlights that sustainability improvements for spirulina must target process engineering (e.g., low temperature drying, efficient mixing design) and input sourcing (e.g., alternative carbon sources like captured CO_2) rather than agronomic practices.

Finally, the one-way sensitivity analysis reinforces the hotspot interpretation: climate results are most sensitive to grid electricity consumption (mixing/aeration, pumping, and drying) and to sodium bicarbonate supply, while changes in other inputs have comparatively smaller leverage at ±20%. From an improvement perspective, this prioritizes (i) process energy efficiency (especially low temperature drying and mixing optimization) and (ii) decarbonization of electricity supply (higher PV share or renewable procurement), together with exploring alternative inorganic carbon strategies (e.g., captured CO_2) to reduce dependence on industrial sodium bicarbonate.

4.2 Social sustainability in context

The SAFA assessment revealed excellent performance particularly in livelihood and human safety and health themes, and good performance in fair trading practices, labor rights, and equity. These results should be interpreted with recognition of potential self-reporting bias in interview-based assessments; future studies would benefit from third-party audits or longitudinal monitoring. The consumer survey, while limited to a small, local sample ($N = 38$), provides contextual insights from the local survey aligned with the SAFA findings, indicating within this specific market context, high product awareness and strong health-related motivations among engaged citizens. This duality, between strong producer-level practices and varied consumer perceptions, underscores the multifaceted nature of social sustainability in niche food systems (El Bilali et al., 2020). Compared to broader Italian agricultural labor benchmarks (CREA, 2023), the enterprise's labor metrics (€124,200 labor income, €103.26/h revenue per labor hour, Table 6) indicate favorable working conditions within its high-tech operational model, However, perceptions of affordability were mixed, and cultural connections were not strongly established, suggesting areas where enterprise communication and community engagement could be enhanced. These case-specific insights underscore the importance of complementing standardized social assessments (SAFA) with localized perceptual data to inform tailored business and communication strategies. In addition, these results highlight spirulina's potential to contribute to social sustainability goals, including decent work and community wellbeing (Zahm et al., 2008; FAO, 2014; El Bilali et al., 2020). As such, organic spirulina can serve as a model for socially responsible agri-food innovation, but policies to improve affordability and consumer education are needed to broaden access.

TABLE 6 CBA indicator results.

Indicator	Value
Total variable costs	€379,506.68
Total revenues	€712,500.00
Gross margin	€332,993.32
Total fixed costs	€187,109.09
Total costs	€566,615.77
Profit tax	€35,012.22
Net income before profit tax	€145,884.23
Net income	€110,872.02
NI/m^2	€36.47
Revenues/m^2	€234.38
Revenues/Total cost	1.26
NI/Total cost	0.20
Labor days	1,150
Labor Unit (2,300 h = 1 LU)	3.00
Labor income	€124,200.00
Revenues/Labor hour	€103.26
Labor cost/m^2	€41.13
Revenue/LU	€237,500.00
NI/Revenue	0.16
Gross margin/labor hour	€48.26

4.3 Economic positioning and scalability

Economic benchmarking (Table 7) shows that spirulina's revenue per m^2 (€234.38) vastly exceeds conventional farming (€0.42/m^2) and dairy (€0.70/m^2). A more structurally relevant comparison with high-intensity greenhouse vegetables (estimated €45/m^2) still shows spirulina's superior areal productivity, though the gap is less extreme. This reflects spirulina's biorefinery-like production model rather than direct comparability with traditional agriculture. Scalability is constrained by several factors: high sensitivity to energy costs (electricity constitutes a major operational expense), dependence on premium market positioning, and need for technical expertise. However, spirulina's high labor productivity

TABLE 7 Organic spirulina benchmarking with Italy's agriculture sector.

Metrics	Italy's average for farming business*	Dairy cattle*	Greenhouse vegetables (high-intensity)**	Organic spirulina***
Farm revenue	€87,545	€269,275	€180,000	€712,500
Revenue/m^2	€0.42	€0.70	€45.00	€234.38
LU count	16.7	96.4	4.5	3.0
Revenue/LU	€5,238	€2,792	€40,000	€237,500
Net income/LU	€2,124	€1,036	€12,000	€36,957.33
Net income	€35,501	€99,873	€54,000	€110,872.02

Sources: *Italian averages (farming and dairy): CREA (2023). **Greenhouse vegetable estimates: Derived from CREA (2023) and ISMEA (2023) aggregated data for high intensity protected horticulture in Southern Italy. ***Organic spirulina: Primary data from the case study.

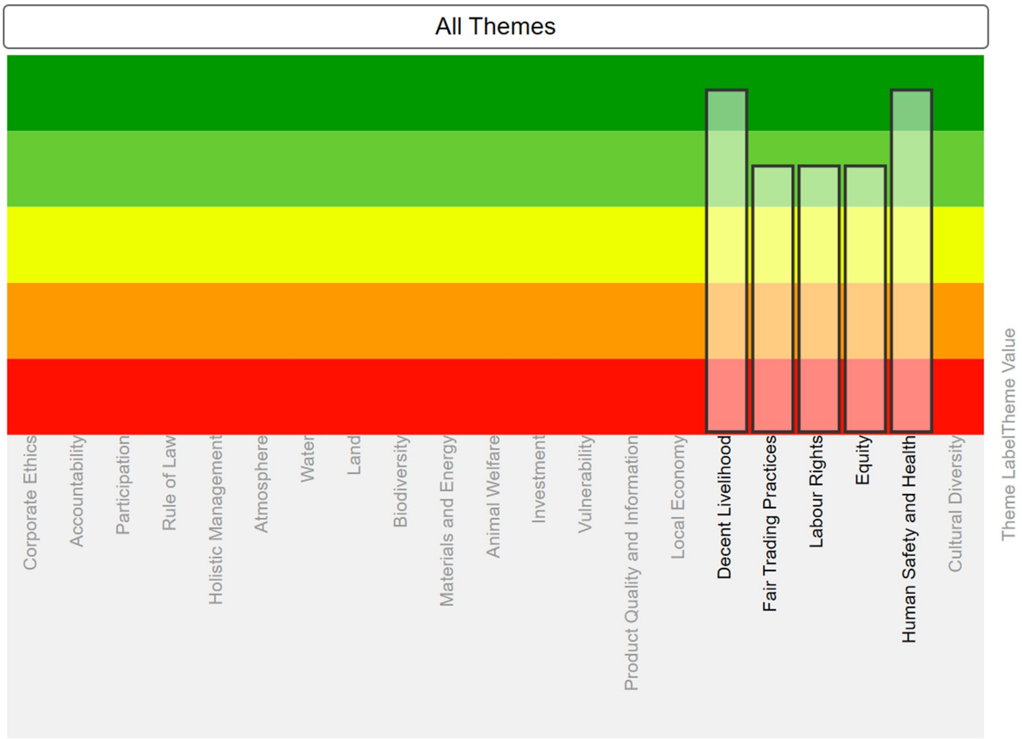


FIGURE 4
Social wellbeing results per theme, sub-theme, and indicator.

TABLE 8 **Comparison of organic spirulina GWP results with two different conventional spirulina cultivation scenarios.**

Factor	Organic spirulina	Standard year-round scenario	Seasonal operation scenario
Total GWP	15.049 kg CO_2-eq	28.2 kg CO_2-eq	15.5 kg CO_2-eq/kg
Electricity contribution	7.21 kg CO_2-eq (47.97%)	12.4 kg CO_2-eq (44%)	44% of total GWP (around 6.8 kg CO_2-eq)
Sodium bicarbonate	4.56 kg CO_2-eq	8–25% contribution (approx. 2.25–7.05 kg CO_2-eq)	8–25% of total GWP (around 1.24–3.87 kg CO_2-eq)
Other nutrients (NPK, $NaNO_3$)	1.54 kg CO_2-eq	14–34% (approx. 3.95–9.58 kg CO_2-eq)	14–34% contribution to GWP (approx. 2.17–5.27 kg CO_2-eq)
Thermal regulation	Not included	14% (approx. 3.95 kg CO_2-eq)	Not included
Infrastructure	Not a major contributor (not fully identified)	18–36% (approx. 5–10.2 kg CO_2-eq)	18–36% contribution to GWP

(€48.26 GM/labor hour vs. ~€8/h for Italian farms) suggests potential for decent livelihoods within technologically advanced agri-food niches. Electricity-cost sensitivity is material because annual electricity demand across mixing/aeration (15,574 kWh), lab/lighting (3,892 + 3,892 kWh), drying (31,148 kWh), and pumping/treatment (23,360 kWh) sums to 77,866 kWh/year in the case dataset. Using the baseline tariff applied in the CBA inputs (€0.20/kWh), this corresponds to around €15,573/year in electricity expenditure, which is embedded within the reported baseline net income. Holding all other variables constant, net income would increase by around €3,893 under a €0.15/kWh scenario and decrease by around €7,787 under a €0.30/kWh scenario relative to the baseline net income reported for the case.

These findings echo prior studies on microalgae profitability, which emphasize efficiency gains in resource use and market demand for functional foods (Costa et al., 2019; Mkindi et al., 2021). As such, spirulina production can diversify farm income streams and strengthen rural economies, particularly in regions with limited arable land.

Seasonal production adjustments would affect both annualized metrics: production cessation would increase GWP per kg through reduced annual output, while heating would increase absolute emissions. Economic returns would similarly be affected by either reduced revenue (from seasonal stoppage) or increased costs (from heating). These dynamics highlight the importance of climate-adapted cultivation strategies, such as

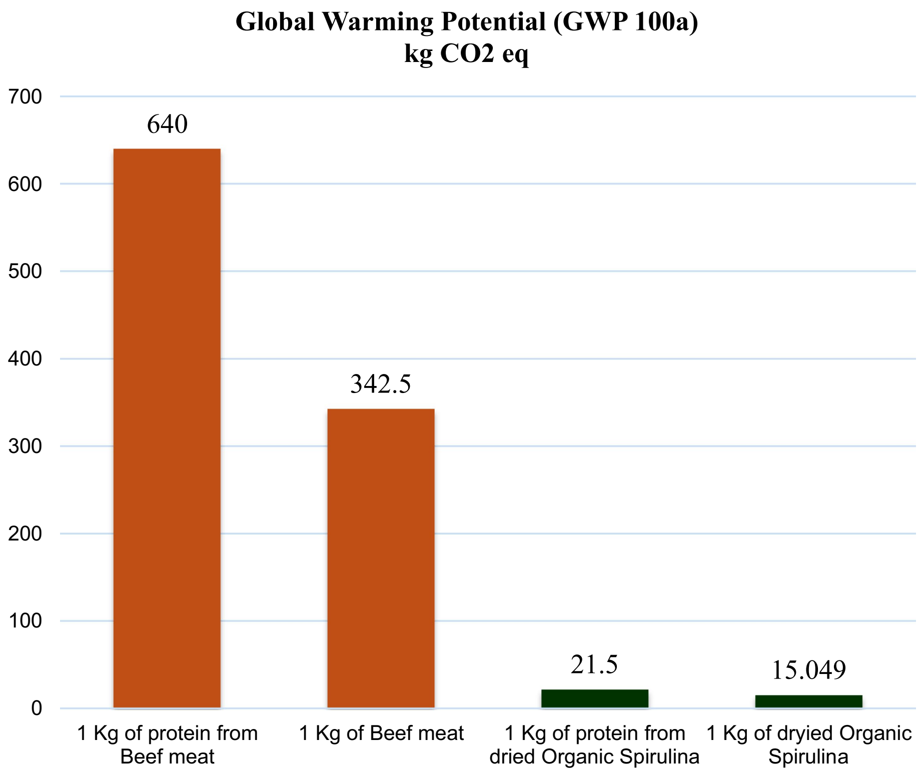


FIGURE 5
Comparison between organic spirulina production with beef production.

seasonal planning or integration with waste-heat sources, to optimize annual sustainability performance.

Furthermore, the economic scalability of this organic spirulina model outside the Italian context depends on several interrelated factors. First, energy costs and sources are critical: in regions with lower electricity prices or higher renewable energy penetration, the operational costs, and thus net income, could be more favorable. Conversely, in areas reliant on fossil-based grids, both economic and environmental performance would diminish. Second, market development varies significantly: while Italy and the EU offer premium markets for organic, functional foods (Annunziata and Vecchio, 2016), other regions may lack consumer awareness or willingness-to-pay, affecting revenue potential. Third, climate conditions influence both productivity and operational costs: warmer climates could reduce or eliminate heating needs, improving annual yields and reducing energy burdens, whereas temperate regions would face seasonal constraints as noted in our limitations. Fourth, policy and subsidy frameworks differ: the EU's Green Deal and Algae Initiative (Gerhard et al., 2023) provide supportive structures that may not exist elsewhere. Moreover, circular economy integration, such as access to treated wastewater or organic waste streams, depends on local infrastructure. Therefore, while the core bioprocessing model is transferable, its economic viability at scale will be context-specific, requiring adaptation to local energy systems, market structures, climate, and policy environments. Consequently, the findings of this study, alongside analyses of socio-economic risks in Mediterranean agriculture (Frem et al., 2021; Cardone et al., 2022; Nardelli et al., 2024), highlight that the transition to sustainable food systems requires models that simultaneously quantify positive sustainability outcomes and potential vulnerabilities.

4.4 Synergies and trade-offs in pursuing a sustainable spirulina system

This tripartite assessment reveals both synergies and trade-offs. The environmental hotspot (electricity) coincides with a major economic cost driver, suggesting that investments in renewable energy (e.g., solar, geothermal) could simultaneously reduce GWP and improve long-term economic resilience (Tzachor et al., 2022). Socially, strong labor performance supports economic viability through workforce stability and quality compliance. However, the "triple win" may be context-dependent: the model's economic viability relies on premium pricing, which may conflict with social goals of accessibility and affordability, as indicated by survey responses (39% found spirulina expensive). Spirulina thus aligns well with circular bioeconomy principles, especially water recycling and nutrient reuse, but its sustainable scaling requires integrated strategies that address energy intensity, market development, and inclusive access.

4.5 Broader implications for processed food sustainability

The integration of spirulina into processed foods (e.g., pasta, snacks, dairy products) offers opportunities to enhance nutritional quality while reducing environmental footprints. Landscape-level approaches (Bozzo et al., 2022) illustrate how spatial and ecological dimensions intersect with economic sustainability, a perspective relevant for scaling spirulina production. As functional food innovation expands, spirulina can contribute to EU policy goals on sustainable consumption and production (Gerhard et al., 2023). The successful evaluation of this organic spirulina model aligns with calls for structured approaches to classify and assess novel agri-food innovations, as highlighted in recent sectoral reviews (Campobasso et al., 2025). As such, promoting spirulina-based processed foods could support healthier diets, reduce reliance on animal proteins, and advance circular bioeconomy strategies.

4.6 Limitations of the study and future research directions

Results are based on one Italian factory, single case study, limiting generalizability. The consumer insights are derived from a small, exploratory sample ($N = 38$) within a localized market and are not statistically representative. Their value lies in providing qualitative context for this single case study, not in generalizable claims about consumer behavior. Findings are therefore presented as descriptive insights to inform local decision-making. Some inputs (e.g., packaging impacts, consumer survey sample size) may not fully capture variability. Seasonal variations in energy and water use were not fully modeled. *The LCA assumed the average national electricity grid mix. Future assessments could explore scenarios with renewable energy integration, which would likely substantially reduce GWP, particularly given electricity's dominant contribution (48%).*

The foreground production and cost dataset used in this study corresponds to the facility's seasonal operating window (April–November) as documented in the case-study data. Therefore, the reported economic and environmental results should be interpreted as performance under seasonal Mediterranean operation, rather than as a forced year-round (winter-heated) scenario. If production is reduced or stopped during winter months, annual output and revenues would decrease and fixed costs would be allocated over fewer kilograms, potentially worsening annualized indicators (e.g., NI per year and impacts per kg when annualized). Conversely, maintaining winter production would likely require supplemental heating and thus higher energy demand, which would increase GWP because electricity is already the dominant contributor to climate impact in this case.

This boundary choice is consistent with comparative evidence reported in the thesis, where seasonal cultivation scenarios show markedly lower climate impacts than year-round thermally regulated scenarios (e.g., 15.5 kg CO_2-eq/kg seasonal vs. 28.2 kg CO_2-eq/kg standard/year-round in a reference ORP system).

The LCA and CBA assume continuous annual production, while in practice, spirulina cultivation in Southern Italy is typically reduced or suspended during winter months (December–February) due to suboptimal temperatures unless supplemental heating is employed. This seasonal variation has dual implications: (i) Economic impacts: Annualized net income (€110,872) likely represents an optimistic scenario, as winter production cessation would reduce annual revenue proportionally. If production stops completely for 3 months, revenues could decrease by approximately 25%, potentially reducing net income to around €83,000–€90,000, depending on fixed cost coverage. Conversely, maintaining winter production with heating would increase energy costs substantially, potentially reducing net income through higher variable costs. The current CBA thus reflects optimal seasonal conditions rather than annual operational reality. (ii) Environmental impacts: The reported GWP (15 kg CO_2-eq/kg) assumes consistent production across seasons. Winter production cessation would effectively increase the carbon footprint per kilogram on an annual basis, as the same facility-level overhead emissions would be allocated to reduced annual output. Alternatively, winter heating, typically from natural gas or electricity, would significantly increase the GWP per kg biomass, particularly given electricity's already dominant contribution (48% of GWP). Previous studies in Mediterranean climates estimate that heating can increase spirulina's GWP by 40–60% compared to seasonal operations (Quintero et al., 2021; Fernández-Ríos et al., 2023). As such, future assessments should implement dynamic LCA and CBA models that account for seasonal temperature variations, heating requirements, and production scheduling to provide more accurate annual sustainability metrics for temperate regions.

Benchmarking against Italian farm averages provides context but may not reflect global competitiveness. In other words, the economic comparison with conventional farm averages, while informative for contextual positioning, should be interpreted with recognition of fundamental structural differences between extensive agriculture and high-tech bioprocessing systems. For future research, assessing spirulina sustainability at larger industrial scales and across diverse geographic contexts merit attention. Also, extend LCA to include downstream processing (e.g., incorporation into pasta, snacks) would be relevant to capture full product footprints. Moreover, exploring consumer willingness-to-pay and long-term adoption patterns for spirulina-based processed foods (Annunziata and Vecchio, 2016) would be interesting to capture consumer behavior. Furthermore, continuous monitoring and surveillance (El Handi et al., 2022), highlight the importance of robust data collection frameworks for sustainability assessments. To propose specific follow-up studies, such as a discrete choice experiment (DCE) for spirulina-based products, mirroring the methodology used in the sea urchin study (Petrontino et al., 2023b) to quantify WTP for specific attributes (organic, local, high-protein). Finally, future research should develop scenario-based techno-economic models that explicitly parameterize scaling factors (e.g., capital expenditure scaling exponents, operational efficiency curves) and incorporate probabilistic forecasts of energy costs to provide more robust guidance for investors and policymakers planning industrial-scale facilities.

5 Conclusion

This study aimed to conduct a tripartite sustainability assessment of organic spirulina production in Southern Italy. In addressing our first objective, the LCA confirmed spirulina's low-carbon profile, with a GWP of 15 kg CO_2-eq/kg biomass, substantially lower than conventional spirulina and vastly lower than beef protein, while the negative water scarcity result reflects the flexibility of using treated wastewater in cultivation, thereby reducing pressure on freshwater resources. Crucially, this advantage is amplified when considering protein equivalence, positioning spirulina as a viable, climate-resilient protein source.

Regarding our second objective, the SAFA assessment revealed robust social performance in decent livelihood and labor rights, while the consumer survey highlighted the dual challenge of high health perception versus affordability barriers, illustrating that social sustainability encompasses both production ethics and market accessibility. For our third objective, the CBA demonstrated clear economic viability and superior labor productivity compared to Italian agricultural averages, though this success is intrinsically linked to a biorefinery model dependent on premium markets and circular inputs.

Considering these findings, organic spirulina production holds clear potential to support broader sustainability agendas, particularly by contributing to the EU Green Deal and the United Nations Sustainable Development Goals (SDGs). Its role as a nutrient-dense, low-footprint protein source directly aligns with SDG 2 (Zero Hunger) by offering an alternative pathway to address malnutrition, while its integration into circular bioeconomy models advances SDG 12 (Responsible Consumption and Production). To fully realize this potential, future development should emphasize technological innovation, including renewable energy integration to reduce electricity burdens, carbon capture strategies to lower emissions, and nutrient recycling systems to optimize resource efficiency. Together, these measures can enhance spirulina's role as a climate-smart, socially responsible, and economically viable ingredient for sustainable processed foods.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors without undue reservation.

Ethics statement

The data collected were used exclusively for statistical purposes and for this study. They will not be disclosed to third parties or used for private interests, own or others, according to Regulation (EU) 2016/679 on the protection of individuals regarding the processing of personal data. The acquired information was exclusively used in an aggregate way, thus guaranteeing the most complete anonymity of the respondent.

Author contributions

AA: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Software, Writing – review & editing. MF: Conceptualization, Formal analysis, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. RR: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Supervision, Writing – review & editing. AC: Data curation, Formal analysis, Software, Writing – review & editing. GC: Conceptualization, Funding acquisition, Supervision, Validation, Writing – review & editing.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2026.1763476/full#supplementary-material

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