Environmental Impact Assessment Review 108 (2024) 107579

Contents lists available at ScienceDirect

Environmental Impact Assessment Review

journal homepage: www.elsevier.com/locate/eiar

Environmental implications and hidden costs of artisanal spirulina (*Arthrospira platensis*) production and consumption

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A R T I C L E I N F O

Keywords:
Life cycle assessment (LCA)
Monetization
Environmental cost accounting
Nutrient rich food
Superfood
Sustainability

A B S T R A C T

This study aims to assess for the first time the environmental interactions of artisanal spirulina production and consumption, addressing a holistic approach by including the nutritional properties within the assessment and an economic analysis. To do so, life cycle assessment is conducted defining the system boundaries from cradle to consumer and two functional units: mass-based (1 kg of product) and nutrient-based (Spanish Nutrient Rich (super)Food 9.2 score). Afterwards, the monetization of the environmental impacts using the 'eco-cost' method and the internalization of externalities to estimate the real cost of spirulina is performed. The purely environmental analysis identifies cultivation as the main hotspot of the product system, reporting a total average carbon footprint of 3.5 kg CO_2 eq./kg, while together with the nutritional model, it reveals the potential of spirulina supplements by reducing the impacts as consequence of its rich nutritional profile. In monetary terms, the internalization of external costs linked to the impacts are trivial compared to the selling price of spirulina; only 3.6€ per kg of spirulina should be invested to avoid the negative effects of its production, while its market price sums up to 217€/kg. This value falls drastically by including the nutritional index in the evaluation, as well as varies significantly when modifying the monetization method, which constitutes a constraint at the same time that a challenge for future studies.

1. Introduction

Global population growth, rising food prices and increasing scarcity of resources are creating an uncertain future for the food sector, which will exacerbate food insecurity and hunger that particularly affect vulnerable citizens (Dinar et al., 2019). The provision of sufficient food will be jeopardized by environmental phenomena (Zhang et al., 2023), which will decline agriculture and livestock yields in many areas due to climatic and other stress factors, endangering the production of commodities and derivatives (Cramer et al., 2018). Indirect effects of this degradation lie in the limited availability of resources; energy shortage limits the production capacity causing negative socio-economic development trends (Xia and Yan, 2022), while the spatial distribution and timing of water availability may be affected by climate change (He et al., 2021). Besides, disruptions of supply chains and fluctuations of food prices add another risk to human health, which are particularly impacted by external events such as pandemic or armed conflicts (Fazle Rabbi et al., 2023). Consequently, the continued pressure on food systems is leading to calls for sustainability transformation. The production and consumption of 'novel foods' – considered as foods produced with innovative technologies, as well as foods traditionally eaten outside the European Union (European Union, 2015) – constitutes an important strand of the transition (Mazac et al., 2023), offering potential synergies between nutritional, environmental, cultural and economic benefits (Conti et al., 2021).

Among these 'novel foods', algae are attractive options that are growing in popularity as part of innovative gastronomy and culinary developments (Figueroa et al., 2021). In recent years, the importance of microalgae, and particularly spirulina (*Arthrospira platensis)*, has stressed as a new nutrient source. Known as the blue-green algae, spirulina has an extraordinary protein content (60–70% by dry weight), and highlights for its richness in vitamins, minerals, essential fatty acids, carotenoids, antioxidants, and phycocyanin (Kumar et al., 2022). Indeed, its characteristics make it considered as 'superfood' or 'functional food', as they go beyond those of basic products (Wells et al., 2017). The active incorporation of spirulina into dietary patterns could have the potential to satisfy specific population nutritional shortfalls, at the same time that provide parallel health benefits like enhancing sleep

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https://doi.org/10.1016/j.eiar.2024.107579
Received 11 March 2024; Received in revised form 15 May 2024; Accepted 10 June 2024
Available online 13 June 2024
0195-9255/

quality or reducing stress (Moradi et al. (2021). Likewise, it could be used to partially replace conventional foods whose production systems transgress some planetary boundaries, such as animal-derived products, reducing the environmental impacts and meeting nutrition and feasible consumption constraints (Mazac et al., 2022). Although it has a long history – already consumed in the 16th century (Lafarga et al., 2020) and first commercialized in the 50's (Kumar Koli et al., 2022) – its production and consumption have been highly regionalized. Spirulina cultivation and transformation have been focused on China, whose factories are characterized by large-scale industrial production, and distinguished by high mechanization and the use of spray-dryers for rapid operation and high productivity (Yang et al., 2022). Even though the economic value of this product is affordable and its environmental implications are comparable to those of other protein-rich conventional products, it fails in the irresponsible use of resources (Ye et al., 2018) as well as in the final nutritional quality of the product. To mitigate such trends, a competitor has emerged, characterized by artisanal production techniques. Europe is at the forefront of this nascent segment of the sector, where France, Italy and Spain have the largest number of companies (Araújo et al., 2020). They are marked by slower but temperature-controlled air-drying and consequently better product quality by avoiding protein denaturation that occurs when working with very high temperatures as in the spray-dryer (Lafarga et al., 2021). Nevertheless, soil, water and air degradation, as well as the consumption of resources, of these traditional practices remain unknown, just like their associated economic implications.

To cope with this, the scientific community is taking important steps towards holistic and integrated approaches to evaluating food systems, render visible their social, economic and natural impacts to develop sustainable action strategies that may limit negative externalities (Castillo-Díaz et al., 2023). Life Cycle Assessment (LCA) presents a tool for the development and improvement of the food industry and comparative research focused on different production techniques and nutrient sources (Padilla-Rivera et al., 2023). To date, several investigations conducted the LCA of spirulina production, albeit few focused on for food purposes. Ye et al. (2018) presents the only research that evaluates the environmental performance of industrial dried spirulina supplements, which besides considers a nutritional perspective. For its part, Tzachor et al. (2022) focuses on improving the environmental profile of *Arthrospira platensis* and analyzed the impacts of a large-scale production in a geothermal plant, obtaining fresh biomass as product instead of the dehydrated algae. With the same objective, Duran Quintero et al. (2021) studies the eco-design of spirulina cultivation using solar systems. Going a step further, some authors conducted the LCA of the recovery of valuable components from spirulina: Papadaki et al. (2017) assesses the recovery of phycocyanin, whereas Cogo Badan et al. (2024) included also the production of exopolysaccharides.

On the other hand, in addition to uncovering the environmental profile of products, LCA serves as a basis for estimating the 'hidden costs' of food systems through the monetization of their environmental burdens (Arendt et al., 2020). Monetization is the conversion of environmental impacts caused by the release of harmful substances or the use of natural resources to monetary units (Canaj et al., 2021). This allows to calculate the real cost of food with methodologies like True Cost Accounting (TCA), which does not only look at the usual financial metrics, but seeks to understand the social, human and ecological impacts of food systems (Baker et al., 2020). This approach presents a necessary pillar for addressing political and economic steering mechanisms to reach set carbon neutrality targets (Ropo et al., 2023). In this regard, Michalke et al. (2023) carries out a comparison of the external costs and true prices of conventional and organic agricultural products, similar to the study of Zhen et al. (2021). Estrada-González et al. (2020) investigates the environmental damage cost to identify the most efficient egg production systems. However, there are no studies evaluating the ecological profile of the artisanal algae, as well as addressing their environmental cost accounting. This gap leads to the inability to compare and reorient systems to minimize their negative consequences while improving socio-economic development and health outcomes.

This article aims to filling this existing gap to find out whether spirulina produced by artisanal means has a good environmental profile, especially in comparison to the industrial product, which translates into lower external costs. Therefore, the objective of this research is to estimate the environmental impacts and associated economic implications of dried spirulina supplements produced by artisanal techniques. Aiming to address a sustainability approach, three key aspects are evaluated with a focus on both producers and consumers: (i) the environmental performance through the development of the LCA, (ii) the economic consequences through the monetization of the impacts and the application of environmental cost accounting, and (iii) the social implications through the consideration of the nutritional contribution of spirulina into the environmental profile. Accordingly, the paper is structured as follows: (i) explanation of the LCA methodology and monetization method, (ii) results, divided into the environmental, nutritional and economic assessments, as well as the sensitivity analyses, and (iii) discussion, which provides a comparison with other products and address the main limitations and challenges of the study. The results of this investigation will provide valuable outcomes for both stakeholders, providing a vision of the advantages and disadvantages of producing the artisanal supplement and evaluating the suitability of including this product into dietary habits.

2. Materials and methods

2.1. LCA methodology

2.1.1. Goal and scope

The final objective of this assessment was the quantification of the environmental impacts of pure dried spirulina supplements produced by artisanal techniques. Parallel goals included the comparison of the systems under study with industrial spirulina production and other Supplements. The lack of studies that encompass this research, as well as the public support from international organizations such as FAO (Food and Agriculture Organization) for the development of small-scale spirulina production for nutritional enhancement, livelihood development and environmental mitigation (Habib et al., 2008), broadens the interest and target audience not only to LCA-practitioners, but to potential producers and consumers.

The product systems were composed of the unitary processes involved in the production of artisanal spirulina in two Spanish companies. This study has a bilateral approach, i.e., the function of the system is to produce and supply dried spirulina, whereas the function of the product is to nurture and provide health benefits. Therefore, to deal with both functions, mass-based and nutrient-based functional units (FU) were defined. Based on the different product formats, 1 kg of dried spirulina in tablets and 1 kg of dried spirulina in noodles were selected as FUs. These FUs were directed towards the producer perspective and were initially selected because they facilitate the comparison between processes and allow an easy interpretation of the results without the need of great scientific knowledge. However, from a consumer point of view, a mass basis might give wrong incentives for an unhealthy but more environmentally friendly nutrition if the content of nutrients differs considerably (Jungbluth et al., 2022). For that reason, a complex nutrient-based FU was defined according to the expected function of spirulina consumption. Since it is commercialized as supplements and perceived by consumers as a complement that helps to guarantee the intake of basic micronutrients, a FU based on the sNRF9.2 (Spanish Nutrient Rich (super)Food 9.2) index (Fernández-Ríos et al., 2024) was defined. Particularly, a FU of 1000sNRF9.2 was used to better display the results. This nutrient profile model measures the adequacy of a food that is considered as an additional source of nutrients outside the diet to deal with the nutritional shortfalls of the Spanish population, and it is estimated with Eq. (1), Eq. (2) and Eq. (3).

$$sNRF9.2_{100g} = sNR9_{100g} - sLIM2_{100g} \quad (1)$$

$$sNR9_{100g} = 100 \cdot \sum_{i=1-9} \left(w_i \cdot \frac{nutrient_i}{DRI_i} \right) \quad (2)$$

$$sLIM2_{100g} = 100 \cdot \sum_{j=1-2} \left(w_j \cdot \frac{L_j}{MRI_j} \right) \quad (3)$$

where w_i and w_j represent the weighting factors for the nutrients to encourage (i = fiber, vitamin B9, D, E and A, Zn, Mg, Ca, Fe) and to limit (j = saturated fatty acids, Na), $nutrient_i$ the amount of nutrient i in 100 g of food, DRI_i the daily recommended intake for nutrient i, L_j the amount of nutrient j in 100 g of food, MRI_j the maximum recommended intake for nutrient j. Values of w_i, w_j, $nutrient_i$, L_j, DRI_i, and MRI_j are reported in Table S.1 of the Supplementary Materials (SM).

The system boundaries were set from 'cradle to consumer' (Fig. 1), and includes the production of spirulina in two Spanish industries located in Lleida, Catalonia (hereinafter SP_LLE) and Valencia (SP_VAL). The manufacture of spirulina supplements is divided in two main stages: the cultivation and the processing. The former consists of the growth of spirulina biomass from the strain inoculum in raceway ponds, to which chemicals are added to act as nutrients, pH regulators, etc., as well as in which light and temperature are controlled. The latter is in turn composed of several stages, starting with the harvesting and followed by successive drying units – filtration, pressing and dehydration – to remove water and concentrate the biomass. Part of the dried product in noodles form is directly packaged for sale, while the other part is converted into tablets and then packaged and distributed. A more detailed description of the system, including culture conditions and processing characteristics, can be found in Section 2 of SM.

Allocation of flows, emissions, and waste is crucial in industrial processes in which coproducts or intermediate waste are generated. Allocation was not necessary for the final products, since the resources for cultivation and drying were divided equally for the two formats commercialized, as reported by the company managers. On the other hand, mass allocation was used for SP_VAL, which generates a small loss at the start of the production cycle. This assignment was avoided for SP_LLE because it operates continuously throughout the year. However, in SP_LLE a mass allocation was applied as only 25% of the total production is sold as dried algae (50% in pills and 50% in powder), whereas the remaining 75% is marketed as fresh biomass, which is out of the scope of the study.

2.1.2. *Data acquisition, assumptions and life cycle inventory*

Primary data were reported by the two producers through questionnaires, taking information from the productive years 2021 and 2022. It included information on the quantity and origin of water, chemicals, or packaging materials, machinery power and time of use, land occupation and main distribution destinations, along with other technical aspects related to the cultivation conditions. The main difference between the companies lies in the type of electricity; SP_LLE produces 75% of their own electricity by solar panels installed on the roof of its facilities and the remaining 25% is obtained from the grid mix, while SP_VAL uses 100% electricity with renewable guarantee of origin, i.e., produced from a mix of renewable sources. The life cycle inventory (LCI)

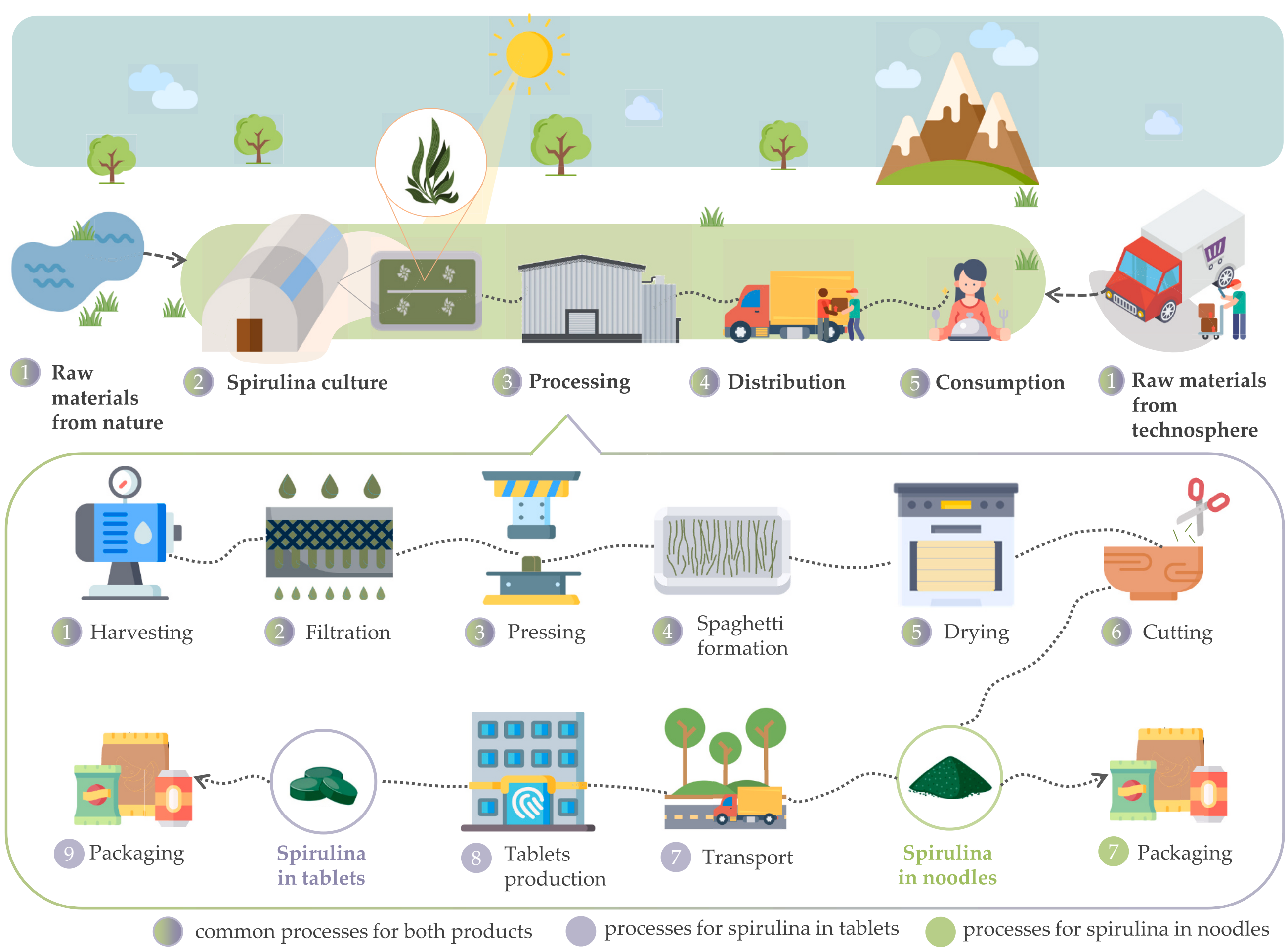

Fig. 1. Flow diagram of the systems under study. It includes production of raw materials, cultivation, processing, distribution and consumption. Adapted from Fernández-Ríos et al. (2023). Icons compiled from Flaticon (2023).

Table 1
LCI for spirulina supplements production, provided per 1 kg spirulina tablets or noodles. The resource quantities are common for both products unless explicitly stated otherwise.

Material	Unit	SP_LLE	SP_VAL
Inputs from nature			
Water, for ponds	m^3	0.22	0.18
Inputs from Technosphere			
Nutrients			
NaCl	kg	0.26	0.70
Distance for NaCl supply	km	168	263
$NaHCO_3$	kg	0.28	1.41
Distance for $NaHCO_3$ supply	km	168	3074
H_3PO_4 (*Laminaria digitata* extract)	L	$2.00 \cdot 10^{-2}$	$5.00 \cdot 10^{-2}$
Distance for H_3PO_4 supply	km	1123	1467
$MgSO_4 \cdot 7H_2O$	kg	$1.33 \cdot 10^{-2}$	0
Distance for $MgSO_4 \cdot 7H_2O$ supply	km	1663	–
Chelated metal compounds	kg	$7.00 \cdot 10^{-4}$	$1.76 \cdot 10^{-3}$
Distance for chelated metal supply	km	GLO*	60
Solution 10% Fe	kg	0	$1.76 \cdot 10^{-5}$
Distance for solution 10% Fe	km	–	0
K_2SO_4	kg	$6.66 \cdot 10^{-2}$	0
Distance for K_2SO_4 supply	km	477	–
CO_2	kg	1.6	1.6
Distance for CO_2 supply	km	62	379
Electricity			
Mixers	kWh	9.73	3.71
Ultraviolet lamps	kWh	0.83	–
Harvest and recirculating pumps	kWh	3.00	0.32
Filtration engine	kWh	$6.00 \cdot 10^{-2}$	0.22
Vacuum pressing	kWh	0.10	$7.37 \cdot 10^{-2}$
Dehydrator	kWh	0.31	0.31
Pressing, for tablets production	kWh	0.56	0.56
Distance to lab	km	600	1100
Packaging			
Cardboard and vegetable PE bags	kg	0.21	0
Distance for cardboard bags	km	252	–
Cellulose and vegetable PE bags	kg	0	$6.25 \cdot 10^{-2}$
Distance for cellulose bags	km	–	1950
Distribution			
Cardboard boxes	kg	$3.66 \cdot 10^{-2}$	0.18
Distance for boxes supply	km	180	350
Cardboard envelopes	kg	0	0.15
Distance for envelopes supply	km	–	350
Kraft paper	kg	$2.38 \cdot 10^{-3}$	0
Distance for paper supply	km	180	–
Distribution radio – national	km	400	400
Distribution radio – local	km	10	–
Outputs to nature			
Emissions to air			
CO_2	kg	0.24	0.24
Outputs to Technosphere			
Wastewater, to treatment	m^3	$6.00 \cdot 10^{-2}$	$1.95 \cdot 10^{-3}$
Residual biomass	kg	0	$5.00 \cdot 10^{-3}$
Packaged spirulina in tablets or noodles	kg	1	1

* Raw material supply is estimated by the processes with location 'GLO' from the ecoinvent database.

(Table 1) included both emissions associated with the resources use and upstream impacts related to inputs production; infrastructure was excluded from the study. Secondary data on upstream processes were collected from the Ecoinvent v3.8 database (Moreno Ruiz et al., 2018) (Table S.2 of SM).

Information regarding the amount of water evaporated was unknown by the industries. In view of the rates reported in other studies, e.g., a loss of about 2% of the total water in the ponds to produce 1 metric ton of tablets (Ye et al., 2018), this evaporation was considered negligible. Direct emissions to water were not included in the assessment since the cultivation takes place in isolated ponds and the wastewater is directed to treatment plants before being dumped into the ocean. Likewise, atmospheric emissions of N_2O and NH_3 caused by the volatilization of nitrogen compounds from chemicals were discarded due to the lack of trustable emission factors (Morales et al., 2019). On the contrary, CO_2 emissions occur inevitably in raceway ponds because the poor efficiency of the injection system and the natural outgassing from the growth medium (Morales et al., 2019). Therefore, transmission of carbon to the culture was assumed to be done with an efficiency of 85%, i.e., 15% of the CO_2 injected into the ponds is diffused to the air (Quinn et al., 2014). On the other side, as tablets production is performed by an external laboratory located in France, which manufactures pure spirulina pills without additives, data on electricity consumption of the pressing was unavailable from the algae producers. Therefore, it was estimated from Ye et al. (2018), who provided an energy use of 320 kWh per ton of tablets. In this case, electricity from the French grid mix was used. In addition, it was considered that both industries use a similar dehydrator with a power of 5.2 kW, based on the data provided by the SP_LLE manager. In relation to the background systems, some modifications of the database were made to adapt the processes to our conditions. These adaptations of the background processes are described in Table S.3 of SM.

2.1.3. Life cycle impact assessment

The conversion of material and energy flows into environmental impacts was performed using the SimaPro v9.3. software. The selection of midpoint assessment indicators was based on the recommendations reported in the Product Environmental Footprint Category Rules (PEFCR) (European Commission, 2017), which are comprised in the Environmental Footprint 3.0 (EF 3.0) method. Based on the systems characteristics and their potential environmental consequences, different impact categories addressing two main areas of protection – natural environment and natural resources – were used, including indicators measuring the fossil energy, minerals and metals use, the acidification and eutrophication (freshwater, marine and terrestrial) potential, the freshwater ecotoxicity and the climate change. In addition, considering that it is not a conventional agricultural system characterized by the intensive use of land, albeit it is cultivated in ponds with water, the scarcity of this resource was considered by means of the Baseline Water Stress (BWS) method (Hofste et al., 2019), which measures total annual withdrawals (blue water) expressed as a percent of the total annual available flow (green water). This method was chosen to be consistent with the economic analysis method. Finally, a Monte Carlo simulation was conducted since it is the most adequate approach to integrate uncertainty in LCA (Santos et al., 2022), taking a 95% coverage probability and using a total of 1000 iterations. Results from this assessment are included within the LCA results.

2.2. Economic analysis

The economic assessment was conducted in two steps. Firstly, the measurement of the environmental pricing of artisanal spirulina production. This reflects the environmental cost that is not included in the market price of goods and which is calculated through the monetization of the impacts. To perform the analysis, monetization factors from 2023 of the Eco-Costs/Value-Ratio (EVR) model were used since it is developed within the European context and it is mainly based on the impact categories considered in the Environmental Footprint method (Sustainability Impact Metrics, 2023) (Table 2). This method adopts an abatement cost perspective and estimates the costs required to reduce pollution and resource depletion according to legislative regulations (Van Fan et al., 2021). Therefore, it is based on the total marginal prevention costs (Phu Giang et al., 2022) and links life cycle impact assessment metrics and aggregated non-market valuation models, enabling the support of decision-making regarding social legislation and intervention schemes (Greenfeld et al., 2021). An explanation of the monetization of the different indicators can be found in Table S.4 of SM. Calculations of the eco-cost of ecosystems (acidification, eutrophication

Table 2
Monetization factors ('eco-costs' 2023) for each environmental impact category (Sustainability Impact Metrics, 2023).

Impact category	Unit	Monetization factor
Climate change	€/kg CO_2 eq.	0.123
Acidification	€/mol H^+	7.08
Eutrophication, freshwater	€/kg P eq.	15.32
Eutrophication, marine	€/kg N eq.	22.12
Eutrophication, terrestrial	€/mol N eq.	1.58
Ecotoxicity, freshwater	€/CTUe	$1.33 \cdot 10^{-2}$
Water scarcity	€/m^3 eq.	1.06
Metals use	–	See Table S.5 of SM
Fossil resources use	–	See Table S.6 of SM

and ecotoxicity), of global warming, as well as of water use, were conducted by the multiplication of the environmental impacts and the corresponding monetization factor. On the other hand, monetary estimations for resource scarcity-related categories were estimated using the inventory data provided by the LCA software and the specific monetization factor for each element or flow, which are compiled in Table S.5 and Table S.6 of SM.

The second step consisted of the calculation of the 'true cost' of artisanal spirulina through environmental cost accounting. While the eco-cost would be useful for producers in knowing the economic implications of their impacts, this approach would provide valuable information to consumers by internalizing external costs into the market price of products, i.e., combining the monetary environmental valuation and the production costs (Michalke et al., 2023). For this assessment, the price gap or external costs were based on the 'eco-costs' previously estimated, whereas the market price was taken from the products commercialized by the companies under study, of 185€ (SP_VAL) and 175€ (SP_LLE) per kg of spirulina in noodles, and 197.5€ (SP_VAL) and 236.5€ (SP_LLE) per kg of spirulina in tablets.

2.3. Sensitivity analysis

The uncertainty arisen from modeling choices, assumptions and methods was analyzed by changing parameters and variables that are expected to have a notable influence on the results. Table 3 shows the parameters set in the baseline scenario and modified in the sensitivity analyses. For simplicity and better understanding, these analyses were carried out for the FU of 1 kg of product. Given the background of the study, it was of particular interest to assess the influence of distribution on the environmental profile of the products. The purpose of this analysis, in addition to evaluating the reaction of the system, is based on studying the suitability of the decentralization of spirulina production. Since this novel food is increasingly consumed in an important part of the world, the need to globalize and adapt its production to different regions to avoid long supply chains and the environmental burdens linked to exports and imports is evident. On the other hand, the economic analysis also underlies some uncertainties mainly based on the pricing method. For that reason, a sensitivity analysis was performed by varying the monetization factors; three costing approaches were applied

Table 3
Parameters defined in the base case and in the scenarios for the sensitivity analyses.

		Environmental analysis	Economic analysis
Base case		National distribution	Eco-Costs/Value-Ratio 2023
Sensitivity analysis	#1	Global distribution	Eco-Costs/Value-Ratio 2023
	#2	National distribution	Eco-Costs/Value-Ratio 2022
	#3	National distribution	Environmental Prices Handbook 2023 (average)

to illustrate the manifold possible interactions on climate costs. The first was based on the application of the 'eco-costs' from 2023, constituting the baseline case. These factors have been updated in 2023 due to the large change in inflation because of the war in Ukraine, whereas they are normally updated every five years (Sustainability Impact Metrics, 2023). Therefore, the analysis was carried out with the 2022 monetization values to see the influence of this externality. Additionally, the monetization factors of the Environmental Prices Handbook 2023 (CE Delft, 2023) were applied. To do so, the quantification of the environmental impacts was conducted using the ReCiPe midpoint (H) 2016 method (RIVM, 2011). In contrast to the EVR method that estimates the monetization factors based only on the abatement costs, the Environmental Prices consider the abatement and damage costs perspectives. While the abatement approach is based on the marginal costs of prevention, the damage cost perspective values the external costs based on the damage estimated, so the selection of the method is likely to have a strong influence on the results (Arendt et al., 2020).

3. Results

3.1. Overview of the LCA results

3.1.1. Producer-oriented analysis (FU: 1 kg of product)

The environmental impacts of the production and consumption of 1 kg of artisanal spirulina in noodles and tablets are illustrated in Fig. 2, along with the contribution of each life cycle stage to the overall burdens. This comparison evidenced that the production of spirulina in tablets entails slightly higher environmental impacts than that of spirulina in noodles, which is caused by the additional stages of transport to the lab and the energy consumption for pressing the pills. This is especially notable in the indicators related to climate change and fossil resources use as consequence of the production of fuel and its combustion. Accordingly, the processing stage – involving from harvesting to packaging – presented a meaningful contribution to the fossil resources depletion (6–38%), especially when tablets are produced. This contribution was also significant in the metals and minerals use, ranging from 24% to 46% and mainly linked to the production of packaging materials, while it was situated between 0.5% and 23% for the remaining impact categories. For its part, the cultivation stage was identified as the main driver of environmental degradation in all indicators, led by the production of chemicals acting as nutrients and pH regulators, especially CO_2 and sodium bicarbonate, and the extraction of water from natural reservoirs in the case of the water scarcity indicator. It is worth noting that the priority use of electricity from renewable sources presents a benefit for the systems, as the impacts caused by energy consumption were trivial. Regarding the distribution stage – including the secondary packaging for shipping and the transport – it reported relatively low impacts with maximum contributions of 22%, predominantly from the production of cardboard boxes and envelopes, whereas the consumption of spirulina no impacted since it is a direct intake without the need for additional resources. Another interesting outcome of the analysis is that the artisanal spirulina produced in the SP_LLE plant showed between 36% and 89% lower environmental burdens than that produced in the SP_VAL for almost all impact categories. This is primarily associated with less intensive use of resources as the plant operates on a continuous mode and allows for greater recyclability and efficiency in the use of chemicals. This fact is especially notable in the acidification and eutrophication indicators, which were highly influenced by the use of sodium bicarbonate. The only exceptions are in the categories of fossil resource use, due to the 25% of energy coming from the Spanish grid, and water use, due to the larger size of the cultivation ponds to ensure better solar contact and biomass growth.

In terms of values, the carbon footprint of spirulina in noodles averaged 3.24 kg CO_2 eq./kg, while that of spirulina in tablets 3.91 kg CO_2 eq./kg. Another relevant issue of these systems lies in the water use, which ranged 0.14–0.16 m^3 eq./kg, which seems quite intensive. Linked

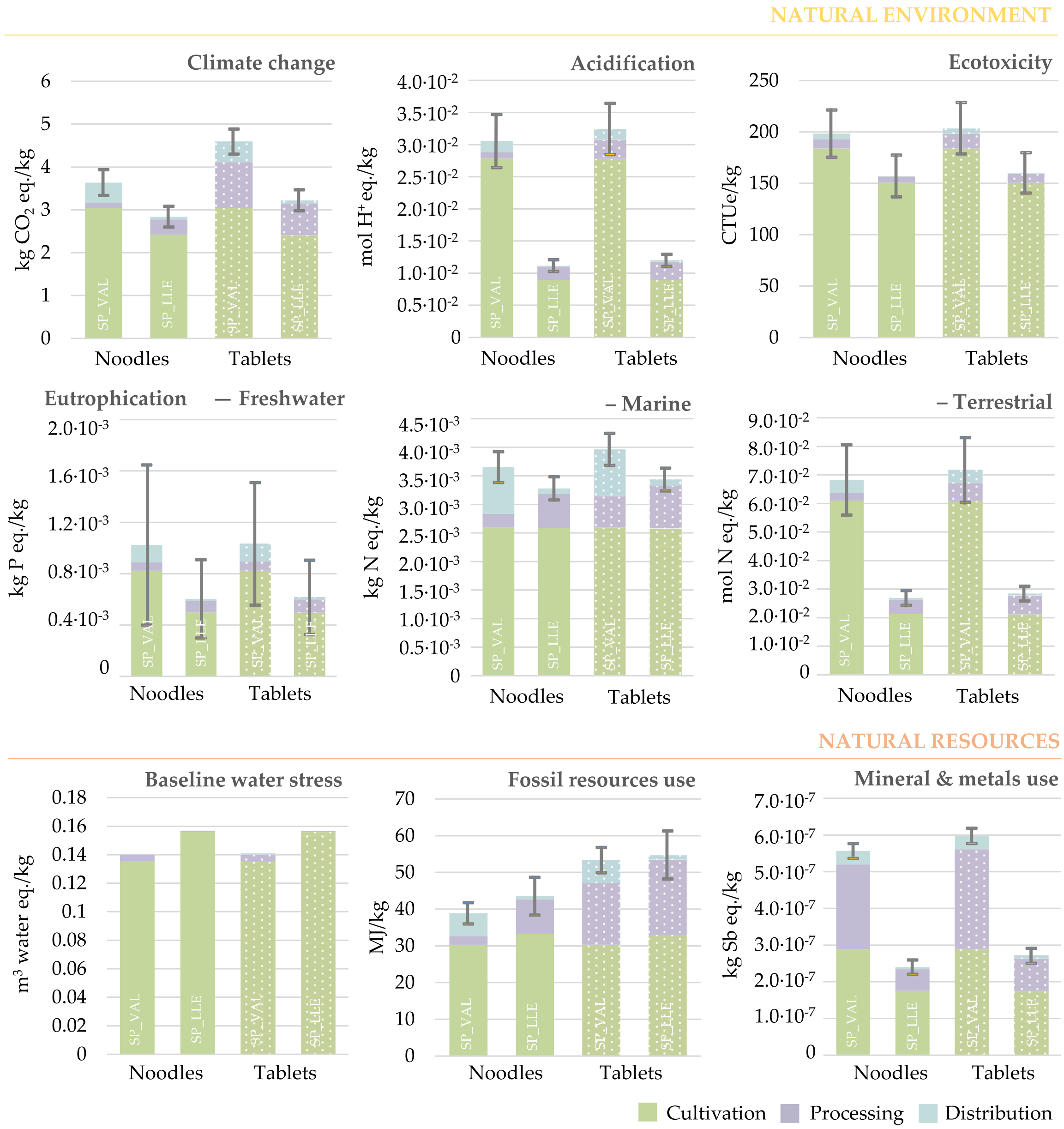

Fig. 2. Environmental performance and contribution of each life cycle stage to the total impacts. Values are reported considering a FU of 1 kg of product; full-colored bars represent spirulina in noodles and dotted bars spirulina in tablets. Standard deviations were estimated by the Monte Carlo simulation. Deviation of the water footprint results was omitted in the graph to avoid distortion of the representation.

to this resource, the ecotoxicity of freshwater added up to between 157 and 203 CTUe/kg of dried spirulina. The fossil resources use accounted for 41.19 MJ/kg noodles and 54.05 MJ/kg tablets, and the minerals and metals use summed up to $3.98{\cdot}10^{-7}$ kg Sb eq. and $4.34{\cdot}10^{-7}$ kg Sb eq. per kg of noodles and pills respectively. Finally, dried spirulina had an average acidification potential of $2.15{\cdot}10^{-2}$ mol H+ eq./kg, while the impacts of eutrophication rose to $8.19{\cdot}10^{-4}$ kg P eq., $3.58{\cdot}10^{-3}$ kg N eq. and $4.88{\cdot}10^{-2}$ mol N eq. per kg.

3.1.2. *Consumer-oriented analysis (FU: 1000sNRF9.2)*

Based on the nutritional composition of artisanal spirulina, the $sNRF9.2_{100g}$ score was estimated at 668, which evidences its health properties and great potential for meeting some nutritional deficiencies. As a frame of comparison, high-scored conventional foods such as wheat, white bean or pistachio achieve scores of 283, 537 and 310, respectively. At this point, it is highlighted the influence of the processing techniques in the final product quality; whereas the spray-drying is carried out at very high temperatures that could produce the protein denaturation and loss of other micronutrients and functional compounds (Ramírez-Rodrigues et al., 2021), longer, temperature-controlled drying allows for better preservation of the algae properties (Soni et al., 2017). This makes the sNRF9.2 scores of industrial and artisanal spirulina differs considerably (335 vs 668). Consequently, the environmental footprint of artisanal spirulina benefits from a nutritional FU. Greenhouse gas emissions of artisanal spirulina in noodles and pills accounted for 0.42–0.54 kg CO_2 eq. and 0.48–0.68 kg CO_2 eq./1000sNRF9.2, respectively (Table 4). Impacts on ecotoxicity averaged between 26.61 and 27.21 CTUe per 1000sNRF9.2, while the consumption of fossil resources summed up to 6.16–8.08 MJ. Impacts on other environmental categories considering this FU are reported in Table 4.

Table 4
Environmental impacts of spirulina production considering a FU of 1000sNRF9.2.

Impact category	Spirulina in noodles		Spirulina in tablets	
	SP_VAL	*SP_LLE*	*SP_VAL*	*SP_LLE*
Climate change (kg CO_2 eq.)	0.54	0.42	0.68	0.48
Acidification (mol H^+ eq.)	$4.57 \cdot 10^{-3}$	$1.67 \cdot 10^{-3}$	$4.85 \cdot 10^{-3}$	$1.79 \cdot 10^{-3}$
Ecotoxicity (CTUe)	29.70	23.53	30.46	23.97
Freshwater eutrophication (kg P eq.)	$1.53 \cdot 10^{-4}$	$9.05 \cdot 10^{-5}$	$1.54 \cdot 10^{-4}$	$9.20 \cdot 10^{-5}$
Marine eutrophication (kg N eq.)	$5.47 \cdot 10^{-4}$	$4.91 \cdot 10^{-4}$	$5.93 \cdot 10^{-4}$	$5.14 \cdot 10^{-4}$
Terrestrial eutrophication (mol N eq.)	$1.02 \cdot 10^{-2}$	$4.02 \cdot 10^{-3}$	$1.07 \cdot 10^{-2}$	$4.25 \cdot 10^{-3}$
Baseline water stress (m^3 eq.)	$2.10 \cdot 10^{-2}$	$2.35 \cdot 10^{-2}$	$2.11 \cdot 10^{-2}$	$2.35 \cdot 10^{-2}$
Fossil resources use (MJ)	5.81	6.51	7.98	8.19
Minerals & metals use (kg Sb eq.)	$8.33 \cdot 10^{-8}$	$3.59 \cdot 10^{-8}$	$8.94 \cdot 10^{-8}$	$4.05 \cdot 10^{-8}$

3.2. Monetization of environmental impacts and internalization of external costs

Fig. 3 depicts the monetarily unaccounted damage from the production of spirulina as well as its real cost considering the market price. The environmental impacts of spirulina production and consumption were translated into an average of 3.49€ per kg of noodles and 3.83€ per kg of tablets. This means that an investment of 3.49€ and 3.83€ would be needed to mitigate the negative effects of *A. platensis* production. These figures are consistent with the environmental profile of the products; the spirulina in tablets entails a higher hidden cost than the spirulina in noodles. Most of the cost stemmed from the ecotoxicity impacts, and followed by climate change, fossil resources use and acidification. Specifically, between 60% and 66% of the investment should be destined to water treatment in municipal facilities to mitigate the impact on ecotoxicity, 10–11% to the installation and use of offshore wind farms to abate carbon emissions, and 6–12% to the replacement of fossil fuel energy with renewable energy. After the internalization of these external costs into the market prices (Fig. 3, right), the true price of artisanal spirulina amounted to 183.36€ per kg of noodles and 220.21€ per kg of tablets. Price gaps only represented approximately 2% of these costs as consequence of the high selling price of spirulina, which in turn is due to the small-scale artisanal production as well as to the low mass contained in the supplements. On the other hand, considering the nutritional FU, the external and true costs were reduced. The former dropped to an average of 0.52€ and 0.57€ for spirulina in noodles and pills, respectively, whereas the latter achieved 27.46€ and 33.03€ per 1000sNRF9.2.

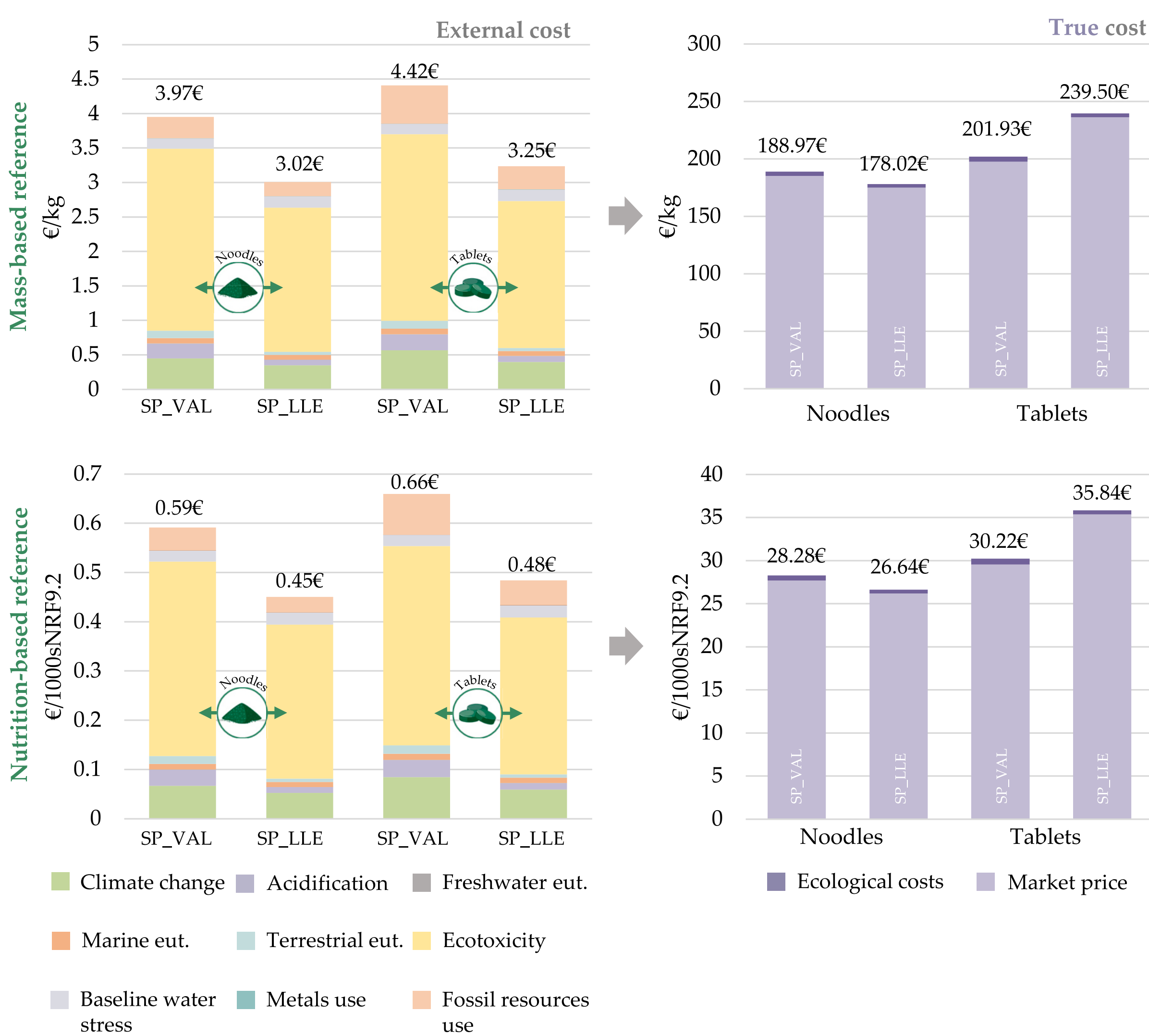

Fig. 3. External costs (left) and total price (market price plus ecological cost) (right) of artisanal spirulina production considering a mass- (top) and nutrition-based (bottom) FUs.

3.3. Sensitivity analysis

3.3.1. Influence of transportation in LCA results

The alternative scenarios compressing both possible exports of artisanal spirulina to main European demanders and imports of the Chinese industrial supplements to Spain, as well as the impacts on climate change of this sensitivity analysis, are illustrated in Fig. 4. Impacts on other categories are reported in Tables S.7-S.10 of SM. According to the assessment, both the type of means of transport and the distance strongly affected the performance of the systems. Exportations by plane entailed the highest greenhouse gas emissions, followed by truck and finally by ship. Moreover, the greater distance, the greater impact. Beginning with the main competitor, China, the commercialization of artisanal spirulina to this country would present an environmental benefit compared to the on-site production and sale if transported by a cargo ship, generating an impact of approximately 3.62 kg CO_2 eq./kg on climate change. In contrast, it did not appear to be environmentally profitable if plane is used as a means of transportation (≈10 kg CO_2 eq./kg). On the other hand, exports to Europe, and particularly to United Kingdom and Germany, did not produce a very significant worsening in environmental performances. In fact, when spirulina is shipped from the port of Barcelona (Spain) to the port of Tilbury (UK), the carbon emissions were even lower than when national distribution is carried out by trucks (3.52 vs 3.57 kg CO_2 eq./kg). When exported to Berlin (Germany), greenhouse gas emissions grew 21% and 27% if transported by truck and aircraft, respectively, compared to the base case. Finally, the impact of the consumption of Chinese industrial spirulina in Spain was analyzed, which is becoming more common due to its more affordable price. In either case, whether transported by air (14.85 kg CO_2 eq./kg) or by the ocean (7.84 kg CO_2 eq./kg), emissions were significantly higher than the production in the country of consumption.

3.3.2. Influence of methodological choices in environmental costs

This section summarizes the main results of the sensitivity analysis conducted by changing the monetization strategy of the impacts. Economic implications based on the abatement ('eco-cost') or damage (Environmental Prices) of the environmental performance of spirulina are illustrated in Fig. 5. The economic analysis proved to be highly sensitive to the cost perspective of the methods. On the one hand, not much difference was observed between the 'eco-cost 2022' and 'eco-cost

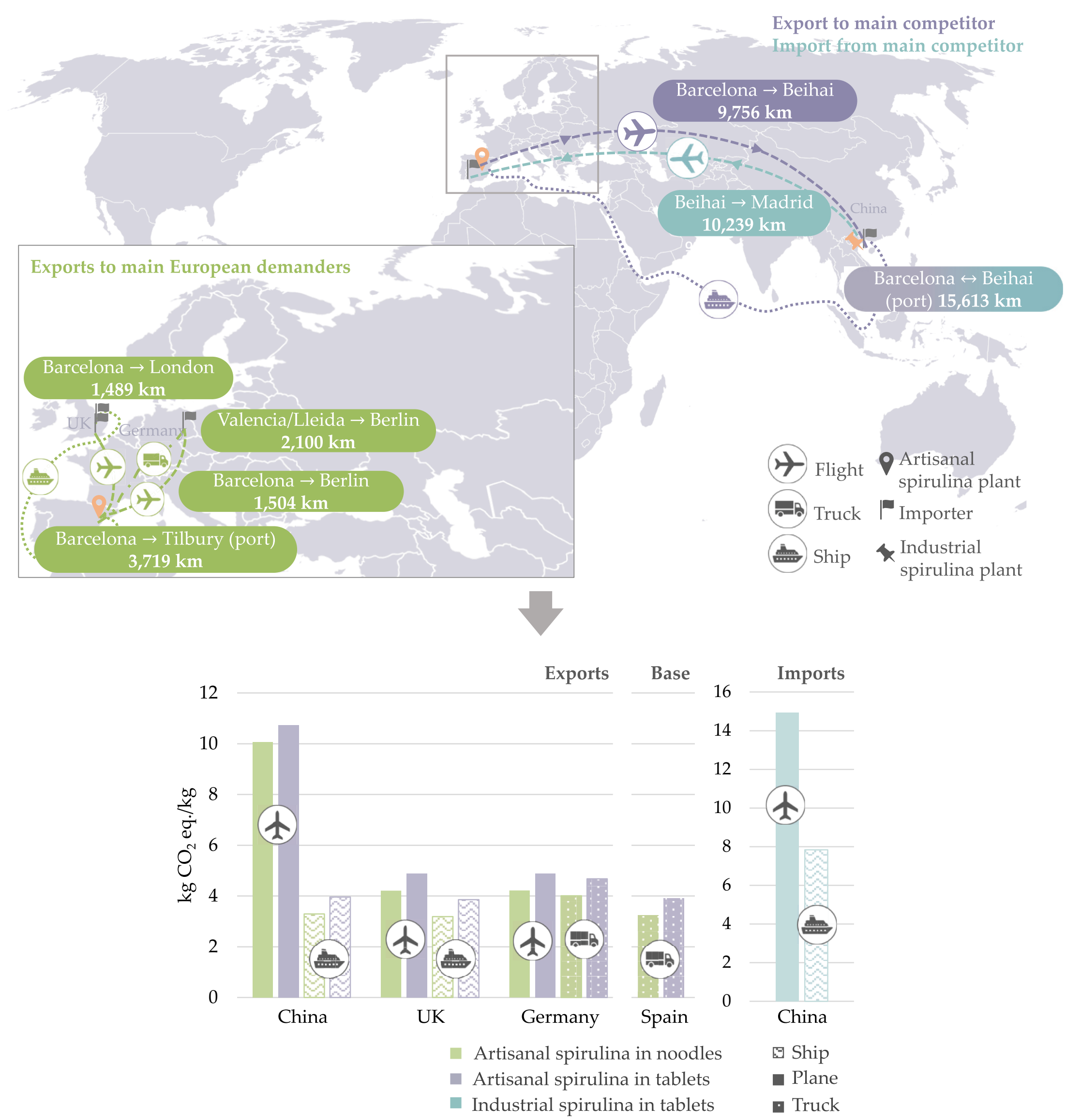

Fig. 4. Scenarios (top figure) and influence of exports of artisanal spirulina and imports of industrial spirulina on climate change (bottom figure). Values are calculated by the average of the results of the two industries under study.

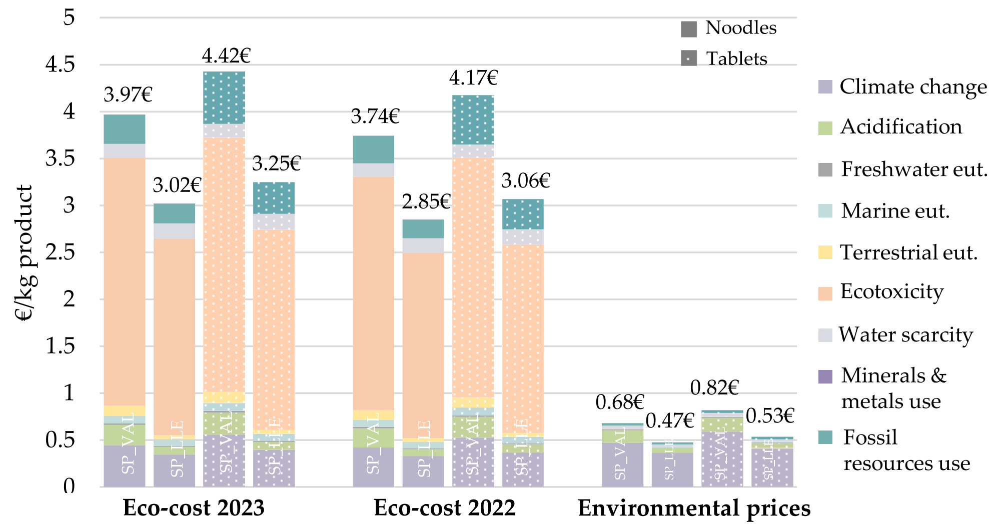

Fig. 5. Results of the sensitivity analysis conducted in the economic assessment. Monetization factors from the 'eco-cost 2022', 'eco-cost 2023' and 'environmental prices 2023' were applied to convert the environmental impacts into monetary values.

2023' and the comparison leads to the expected results: higher external costs were obtained when using the monetization factors of 2023 due to the rise of the core inflation in the EU at 14.2% (Sustainability Impact Metrics, 2023). Specifically, to prevent the emissions and resources scarcity linked to the production of 1 kg of spirulina, 5.65% more should be invested in 2023 than in 2022. The trend remained the same; impacts of the ecotoxicity indicator led the investment, followed by climate change and fossil resources scarcity. On the other hand, costs changed drastically when the monetization method established by the 'Environmental Prices Handbook 2023' was applied. Environmental impacts obtained applying the ReCiPe midpoint (H) 2016 method are reported in Table S.11 of SM. Environmental prices of spirulina in noodles and tablets achieved 0.57€ and 0.67€, respectively. Variation in the results was mainly due to two reasons. Firstly, the LCA method changed, so that the impact categories may consider different substances, and therefore, the environmental impacts on which the economic assessment was based. Secondly, some monetization factors of the Environmental Prices methods are based both on damage and abatement costs perspectives, which means that they can differ significantly from one method to another. For instance, climate change was the main cost driver in this case. The valuation of climate change was estimated by a combination of damage and abatements costs, so even though environmental impacts remain the same since the ReCiPe and EF3.0 methods use the same methodology, the costs calculated with the Environmental Prices were slightly higher than those of the 'eco-cost'. Another important change was observed for the ecotoxicity impacts, whose contribution decreased from up to 66% of the 'eco-cost' to less than 1% due to the estimation of the monetization factor.

4. Discussion

4.1. Interpretation and comparison of LCA results

Establishing a comparison framework for the results obtained is not easy. Based on the outcomes reported in Section 3.1.1., related to the environmental impacts of spirulina production under a FU of 1 kg of product, it can be seen that the carbon footprint is nearly half of the total greenhouse gas emissions reported for a 'cradle to gate' industrial spirulina production in China (7.7 kg CO_2 eq./kg tablets) (Ye et al., 2018). Similarly, in this Chinese study 82% of the carbon burdens come from the cultivation, whereas the rest of the contribution revolves around the processing, in which the use of spray-dryers leads the impact. Unfortunately, comparison with other impact categories was not possible due to differences in the environmental impact method and, consequently, in the methodology for estimating the results. On the other hand, focusing on the function of spirulina as a supplement to satisfy nutritional needs, a comparison can be carried out with other supplements. Although it needs further study, spirulina has opportunities to become a great competitor since it is a non-synthetic product that contains a complete nutritional profile, i.e., it is not a specific vitamin or mineral supplement. For instance, methylcobalamin supplements – ingested to treat vitamin B12 shortfalls – emits around 4.4 kg CO_2 eq. per daily recommended dose, i.e., 1.2 mg. (Cooreman-Algoed et al., 2023), while protein isolate from lupin impacts around 6.5 kg CO_2 eq. per kg (Vogelsang-O'Dwyer et al., 2020). Taking this last reference, greenhouse gas emissions from spirulina would achieve 2.28 kg CO_2 eq./kg protein, providing additionally other essential nutrients such as fiber, vitamin E or Mg. Considering the nutritional FU, a comparison with other 'superfoods' based on preliminary results led us to the conclusion that spirulina shows a good nutritional-environmental balance, at least considering the carbon emissions. Estimating the sNRF9.2 of different 'superfoods' and approaching the climate change impact to this reference, we calculated burdens of 0.82 kg CO_2 eq./1000sNRF9.2 for blueberries (Pérez et al., 2022), or 0.29 kg CO_2 eq./1000sNRF9.2 for quinoa (Cancino-Espinoza et al., 2018). These values place spirulina in the middle, being surpassed by quinoa due to better environmental performance although worse nutritional profile. However, if compared with a conventional food product, e.g., rice with 5.31 kg CO_2 eq./1000sNRF9.2, it can be concluded that introducing spirulina into common dietary habits is plausible. Given the problems of food insecurity, the balance between environmental impacts and the nutritional contribution of this microalgae supplement seems entirely acceptable.

4.2. Interpretation and comparison of environmental costs and price

Based on the results and the scarce literature in this field, the values estimated for the environmental costs (3.49€/kg noodles and 3.83€/kg pills) are in the range of those of more conventional products, with meat heading the list. For instance, pork and poultry have an eco-cost of 4.88€ and 2.69€/kg respectively, while it drops for milk to 0.60€/kg and for green peas to 0.22€/kg (Azarkamand et al., 2024). After the internalization of the external costs, the real price of spirulina summed up to 183.36€ per kg of noodles and 220.21€ per kg of tablets, showing the price gap a negligible contribution. It is expected that the hidden costs of industrial spirulina would be more significant than of the artisanal supplement since it has a more polluting profile and a lower market price due to its massive production. Comparison with other 'superfoods' was not possible due to lack of trustable data, but contrasted with conventional products, similar trends can be observed. Although with much lower values, vegetable products, and especially roots and legumes, report minimum contribution of the price gap to the overall costs, while animal-derived products show contributions up to 60% (Michalke et al., 2023). Introducing the nutritional aspect into these metrics, thus addressing a holistic approach, both the external costs and true price were significantly reduced. In this regard, even though it may be more complex for consumers to understand, this FU adequately represents the product function, and although in isolation does not provide sufficient information for conscious decision making, addressing this approach for different comparable products would be highly valuable to customers. In brief, since it provides greater transparency, reporting environmental, economic and nutritional impacts in a single value allows to discern those products that are healthier, more environmentally sustainable and affordable.

4.3. Limitations and assumptions

This section comprised a summary of the main challenges and limitations found in the development of the environmental and economic analyses. As in any LCA study, uncertainty plays a relevant role in the systems performance. The data compiled from primary sources, the selection of secondary processes from the databases and, especially, the environmental impact assessment method, are prone to add significant uncertainty to the results. In fact, the standard deviation reported for the water footprint was substantial mainly due to the impact method chosen, which is influenced by the regionalization and its characterization factors that already have a generally high inherent uncertainty.

On the other hand, the assumptions made in the modeling can have a great influence on the impacts obtained, as demonstrated in the sensitivity analysis. Although a priori distribution does not have a large contribution to the impact, this involves a simple assessment based on straightforward calculations on the basis of hypothetical scenarios. If applicable, it is clear that if small local factories behave in a more environmentally friendly way than large-scale industries, the decentralization of the production of goods would be advisable to avoid long supply chains. However, this is not always true. For instance, if the impacts of both productions are similar, distribution to points of sale or consumers by truck at a national level would have a greater impact than importing the product if it is transoceanic freighted. Moreover, when it comes to long supply chains, the efficiency factor plays an important role. In intercontinental imports/exports, large quantities of product are transported with larger vehicles and round-trip transportation is used. However, when selling directly to the public, e.g., through Internet shopping, one vehicle is used for the shipment of a single order and only one way, which implies worse environmental performances (Malak-Rawlikowska et al., 2019). Another factor to consider when addressing transportation decisions resides in the deterioration of the product quality and the effect on its shelf-life. Short supply chains help ensuring a better preservation of the product due to reduced transportation time and scarcer load and unload activities and human intervention. In contrast, long supply chains are more likely to generate food loss due to the influence of short product shelf life and higher possibilities to produce mechanical, physical or microbial damage in products as consequence of inadequate transportation systems (Magalhães et al., 2021). Although this is not the case with dehydrated spirulina, the fresh biomass that is also marketed must be consumed within 3 to 5 days of production, so delivery of the product cannot be delayed for environmental reasons. Hence, more exhaustive assessments based on the product traceability are necessary, where attention should be paid to these aspects to evaluate the viability of the alternatives.

Regarding the economic analysis, the idea of true cost and monetarization of externalities is tricky and subjected to strong criticism due to its associated uncertainty. The selection of both the environmental impact method and the monetization factors can have a great influence on the results, as evidenced when comparing the 'eco-cost' and 'environmental prices' methods. The adjustment of the monetary values for inflation and currency creates uncertainty, but even more so the difference of impact categories between different monetization methodologies. As an illustrative example, the 'eco-cost' method monetizes the minerals use at inventory level, whereas the 'environmental prices' considers the environmental impacts to calculate the externalities. Therefore, choosing the most rigorous method according to the scope of the study, i.e., the purpose of evaluation, geographical scope or spatial scale to obtaine accurate results is crucial for maintaining coherence (Arendt et al., 2020). Besides, this study addressed an environmental cost accounting, while a full cost accounting involves both environmental and social impacts. The latter should include issues such as social labor conditions, animal well-being or consumer health in order to avoid significant market distortions and welfare losses for society as a whole (Pieper et al., 2020). Therefore, this assessment may be key to future work in this area.

5. Conclusions

This study revolves around a sustainability measurement of artisanal spirulina production and consumption: LCA is applied in combination with a nutritional profile model and monetization factors to estimate the environmental, social and economic interactions of this novel food. Focusing on the research question, spirulina produced by artisanal techniques was discovered to have a fairly good environmental profile, especially when compared to the industrial product and including nutritional aspects in the analysis. Furthermore, the external costs of the production under study were relatively low, which can be considered negligible when included in the selling price of the supplements.

Delving deeper into the results, from a producer perspective, the cultivation of the algae entails the highest environmental impacts, followed by the processing. In view of this trend, efforts should focus on the optimization of this stage. Some recommendations include improving resource efficiency and recyclability by adopting circular economy principles, e.g., using residual CO_2 streams from food industries to feed the ponds, or seawater that already contains the nutrients (with the necessary pre-treatment) instead of freshwater. The consumer-oriented assessment, i.e., applying the sNRF9.2 model, highlights the potential of spirulina in its role as a nutritional source. It seemed to be competitive with other nutraceuticals, e.g., vitamin supplements, which have similar or higher emissions while providing only one nutrient. These LCA results may serve to motivate producers to switch to artisanal spirulina techniques, whilst demonstrating its potential to be introduced into the dietary habits without causing great damage to the environment as long as filling important nutritional gaps in the population. On the other hand, transforming the environmental burdens into monetary units resulted in an investment of about 3.65€ per kg or 0.54€ per 1000sNRF9.2 to avoid the negative effects of spirulina production. This monetization was of particular interest to the study, serving to create a bridge between research results and reality. The hidden cost together with the commercial price gives consumers valuable information to allow to compare products from a sustainability perspective, making it easier to make decisions towards the cheapest, healthiest and most environmentally friendly option. Besides, it facilitates policymakers to strategize for a better future of the food sector, giving visibility to externalities that currently remain hidden and that have a great impact on socio-economic development and planet health. However, even though these analyses are strongly recommended, the selection of the impact method as well as the monetization factors are of vital importance to achieve consistent and rigorous results, as evidenced in the sensitivity analyses. Therefore, attention should be paid to the needs of the study and the door is left open for the modification and development of methodologies according to the research goals.

CRediT authorship contribution statement

Ana Fernández-Ríos: Conceptualization, Methodology, Investigation, Software, Resources, Writing – original draft. **Jara Laso:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Rubén Aldaco:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **María Margallo:** Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgments

This work was supported by the Spanish Ministry of Science and Innovation through the KAIROS-BIOCIR project (PID2019-104925RB) (AEO/FEDER, UE). Ana Fernández-Ríos thanks the Ministry of Science and Innovation of Spanish Government for their financial support via the research fellowship RE2020-094029. The authors also thank the managers of the spirulina production plants for the provision of data.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eiar.2024.107579.

References

Araújo, R., Vázquez Calderón, F., Sánchez López, J., Costa Azecebo, I., Bruhn, A., Fluch, S., García Tasende, M., Ghaderiardakani, F., Ilmjärv, T., Laurans, M., Mac Monagail, M., Mangini, S., Peteiro, C., Rebours, C., Stefansson, T., Ullmann, J., 2020. Current status of the algae production industry in Europe: an emerging sector of the blue economy. Front. Mar. Sci. 7, 626389 https://doi.org/10.3389/fmars.2020.626389.

Arendt, R., Bachmann, T.M., Motoshita, M., Bach, V., Finkbeiner, M., 2020. Comparison of different monetization methods in LCA: a review. Sustainability 12, 10493. https://doi.org/10.3390/su122410493.

Azarkamand, S., Fernández-Ríos, A., Battle-Bayer, L., Bala, A., Sazdovski, I., Roca, M., Margallo, M., Aldaco, R., Laso, J., et al., 2024. Calculating the True Costs of Protein Sources by Integrating Environmental Costs and Market Prices. Sustain. Prod. Consump. Pre-proof.

Baker, L., Castilleja, G., De Groot Ruiz, A., Jones, A., 2020. Prospects for the true cost accounting of food systems. Nat. Food 1, 765–767. https://doi.org/10.1038/s43016-020-00193-6.

Canaj, K., Mehmeti, A., Berbel, J., 2021. The economics of fruit and vegetable production irrigated with reclaimed water incorporating the hidden costs of life cycle environmental impacts. Resources 10, 90. https://doi.org/10.3390/resources10090090.

Cancino-Espinoza, E., Vázquez-Rowe, I., Quispe, I., 2018. Organic quinoa (Chenopodium quinoa L.) production in Peru: Environmental hotspots and food security considerations using Life Cycle Assessment. Sci. Total Environ. 637-638, 221–222. https://doi.org/10.1016/j.scitotenv.2018.05.029.

Castillo-Díaz, F.J., Belmonte-Ureña, L.J., López-Serrano, M.J., Camacho-Ferre, F., 2023. Assessment of the sustainability of the European Agri-food sector in the context of the circular economy. Sustain. Prod. Consump. 40, 398–411. https://doi.org/10.1016/j.spc.2023.07.010.

Cogo Badan, I., Jung, S., Singh, R., Vivekanand, V., Knappert, J., Rauh, C., Lindenberger, C., 2024. Life cycle assessment of exopolysaccharides and phycocyanin production with *Arthrospira platensis*. Fermentation 10, 163. https://doi.org/10.3390/fermentation10030163.

Conti, M.V., Kalmpourtzidou, A., Lambiase, S., De Giuseppe, R., Cena, H., 2021. Novel foods and sustainability as means to counteract malnutrition in Madagascar. Molecules 26, 2142. https://doi.org/10.3390/molecules26082142.

Cooreman-Algoed, M., Boone, L., Uitterhaegen, E., Taelman, S.E., De Soete, W., Dewulf, J., 2023. Environmental life cycle assessment of nutraceuticals: a case study on methylcobalamin in different packaging types. Sci. Total Environ. 893, 164780 https://doi.org/10.1016/j.scitotenv.2023.164780.

Cramer, W., Guiot, J., Fader, M., Garrabou, J., Gattuso, J., Iglesias, A., Lange, M.A., Lionello, P., Llasat, M.C., Paz, S., Peñuelas, J., Snoussi, M., Toreti, A., Tsimplis, M.N., Xoplaki, E., 2018. Climate change and interconnected risks to sustainable development in the Mediterranean. Nat. Clim. Chang. 8, 972–980. https://doi.org/10.1038/s41558-018-0299-2.

Delft, C.E., 2023. Handboek Milieuprijzen 2023. In: Methodische onderbouwing van kengetallen gebruikt voor waardering van emissies en milieu-impacts.

Dinar, A., Tieu, A., Huynh, H., 2019. Water scarcity impacts on global food production. Glob. Food Sec. 23, 212–226. https://doi.org/10.1016/j.gfs.2019.07.007.

Duran Quintero, C., Ventura, A., Lépine, O., Pruvost, J., 2021. Eco-design of spirulina solar cultivation: key aspects to reduce environmental impacts using life cycle assessment. J. Clean. Prod. 299, 126741 https://doi.org/10.1016/j.jclepro.2021.126741.

Environmental Impact Metrics, 2023. The Concept, Structure, and Midpoint Tables of the Eco-costs for LCA. Available online. https://www.ecocostsvalue.com/ecocosts/eco-costs-concept/ (14 December 2023).

Estrada-González, I.E., Taboada-González, P.A., Guerrero-García-Rojas, H., Márquez-Benavides, L., 2020. Decreasing the environmental impact in an egg-producing farm through the application of LCA and lean tools. Appl. Sci. 10, 1352. https://doi.org/10.3390/app10041352.

European Commission, 2017. PEFCR Guidance Document, – Guidance for the Development of Product Environmental Footprint Category Rules (PEFCR).

European Union, 2015. Regulation (EU) 2015/2283 of the European Parliament and of the council of 25 November 2015 on novel foods, amending regulation (EU)No1169/2011 of the European Parliament and of the council and repealing regulation (EC) No258/97 of the European Parliament and of the council and commission regulation (EC) no 1852/2001. Off. J. Eur. Union 327, 1–22.

Fazle Rabbi, M., Ben Hassen, T., El Bilali, H., Raheem, D., Raposo, A., 2023. Food security challenges in Europe in the context of the prolonged Russian-Ukrainian conflict. Sustainability 15, 4745. https://doi.org/10.3390/su15064745.

Fernández-Ríos, A., Butnar, I., Margallo, M., Laso, J., Borrion, A., Aldaco, R., 2023. Carbon accounting of negative emissions technologies integrated in the life cycle of spirulina supplements. Sci. Total Environ. 890, 164362 https://doi.org/10.1016/j.scitotenv.2023.164362.

Fernández-Ríos, A., Laso, J., Battle-Bayer, L., Amo-Setién, F.J., Abajas-Bustillo, R., Ortego-Mate, C., Aldaco, R., Margallo, M., 2024. A novel nutritional index for life cycle assessment of 'superfoods' to enhance food security and environmental protection. Int. J. Life Cycle Assess. Under review.

Figueroa, V., Farfán, M., Aguilera, J.M., 2021. Seaweeds as novel foods and source of culinary flavors. Food Rev. Int. 39 (1), 1–26. https://doi.org/10.1080/87559129.2021.1892749.

Flaticon, 2023. Available online: https://www.flaticon.es/ (10 January 2024).

Greenfeld, A., Becker, N., Bornman, J.F., Spatari, S., Angel, D.L., 2021. Monetizing environmental impact of integrated aquaponic farming compared to separate systems. Sci. Total Environ. 792, 148459 https://doi.org/10.1016/j.scitotenv.2021.148459.

Habib, M.A.B., Parvin, M., Huntington, T.C., Hasan, M.R., 2008. A Review on Culture, Production and Use of spirulina as Food for Humans and Feed for Domestic Animals and Fish. Technical Report. FAO Fisheries and Aquaculture Circular, p. 1034.

He, C., Liu, Z., Wu, J., Pan, X., Fang, Z., Li, J., Bryan, B.A., 2021. Future global urban water scarcity and potential solutions. Nat. Commun. 12, 4667. https://doi.org/10.1038/s41467-021-25026-3.

Hofste, R., Kuzma, S., Walker, S., Sutanudjaja, E.H., et al., 2019. Aqueduct 3.0: Updated Decision-Relevant Global Water Risk Indicators. Technical Note. World Resources Institute, Washington, DC. Available online at: https://www.wri.org/publication/aqueduct-30. Accessed through Resource Watch, (14 December 2023). www.resourcewatch.org.

Jungbluth, N., Ulrich, M., Muir, K., Meili, C., Solin, S., 2022. Analysis of food and environmental impacts as a scientific basis for Swiss dietary recommendations. Technical report. https://doi.org/10.13140/RG.2.2.28446.41287.

Kumar Koli, D., Gaur Rudra, S., Bhowmik, A., Pabbi, S., 2022. Nutritional, functional, textural and sensory evaluation of *Spirulina* enriched green pasta: a potential dietary and health supplement. Foods 11, 979. https://doi.org/10.3390/foods11070979.

Kumar, A., Ramamoorthy, D., Verma, D.K., Kumar, A., Kumar, N., Kanak, K.R., Marwein, B.M., Mohan, K., 2022. Antioxidant and phytonutrient activities of *Spirulina platensis*. Energy Nexus 6, 100070. https://doi.org/10.1016/j.nexus.2022.100070.

Lafarga, T., Fernández-Sevilla, J.M., González-López, C., Acién-Fernández, F.G., 2020. *Spirulina* for food and functional food industries. Food Res. Int. 137, 109356 https://doi.org/10.1016/j.foodres.2020.109356.

Lafarga, T., Sánchez-Zurano, A., Villaró, S., Morillas-España, A., Acién, G., 2021. Industrial production of spirulina as a protein source for bioactive peptide generation. Trends Food Sci. Technol. 116, 176–185. https://doi.org/10.1016/j.tifs.2021.07.018.

Magalhães, V.S.M., Ferreira, L.M.D.F., Silva, C., 2021. Using a methodological approach to model causes of food loss and waste in fruit and vegetable supply chains. J. Clean. Prod. 283, 124574 https://doi.org/10.1016/j.jclepro.2020.124574.

Malak-Rawlikowska, A., Majewski, E., Was, A., Borgen, S.O., Csillag, P., Donati, M., Freeman, R., Hoàng, V., Lecoeur, J., Mancini, M.C., et al., 2019. Measuring the economic, environmental, and social sustainability of short food supply chains. Sustainability 22, 4004. https://doi.org/10.3390/su11154004.

Mazac, R., Meinilä, J., Korkalo, L., Järvïo, N., Jalava, M., Tuomisto, H.L., 2022. Incorporation of novel foods in European diets can reduce global warming potential, water use and land use by over 80%. Nat. Food 3, 286–293.

Mazac, R., Järviö, N., Tuomisto, H.L., 2023. Environmental and nutritional life cycle assessment of novel foods in meals as transformative food for the future. Sci. Total Environ. 876, 162796 https://doi.org/10.1016/j.scitotenv.2023.162796.

Michalke, A., Köhler, S., Messmann, L., Thorenz, A., Tuma, A., Gaugler, T., 2023. True cost accounting of organic and conventional food production. J. Clean. Prod. 408, 137134 https://doi.org/10.1016/j.jclepro.2023.137134.

Moradi, S., Zobeiri, M., Feizi, A., Clark, C.C.T., Entezairi, M.H., 2021. The effects of spirulina (*Arthrospira platensis)* supplementation on anthropometric indices, blood pressure, sleep quality, mental health, fatigue status and quality of life in patients with ulcerative colitis: a randomized, double-blinded, placebo-controlled trial. Int. J. Clin. Pract. 75, e14472 https://doi.org/10.1111/ijcp.14472.

Morales, M., Collet, P., Lardon, L., Hélias, A., Steyer, J., Bernard, O., 2019. Life-Cycle Assessment of Microalgal-Based Biofuel, in: Biomass, Biofuels and Biochemicals.

Moreno Ruiz, Valsasina, Brunner, Symeonidis, FitzGerald, Treyer, Bourgault & Wernet., 2018. Documentation of changes implemented in the Ecoinvent Database v3.5. Ecoinvent, Zurich, Switzerland.

Padilla-Rivera, A., Hannouf, M., Assefa, G., Gates, I., 2023. A systematic literature review on current application of life cycle sustainability assessment: a focus on economic dimension and emerging technologies. Environ. Impact Assess. Rev. 103, 107268 https://doi.org/10.1016/j.eiar.2023.107268.

Papadaki, S., Kyriakopoulou, K., Tzovenis, I., Krokida, M., 2017. Environmental impact of phycocyanin recovery from *Spirulina platensis* cyanobacterium. Innov. Food Sci. Emerg. Technol. 44, 217–223. https://doi.org/10.1016/j.ifset.2017.02.014.

Pérez, R., Laca, A., Laca, A., Díaz, M., 2022. Environmental behaviour of blueberry production at small-scale in Northern Spain and improvement opportunities. J. Clean Prod. 339, 130594. https://doi.org/10.1016/j.jclepro.2022.130594.

Phu Giang, N., Phuong, Thi Lan, N., 2022. The eco-cost and application of life cycle assessment (LCA) to determine eco-cost and sustainable level of enterprises. J. Posit. Sch. Phychol. 6 (7), 2924–2940.

Pieper, M., Michalke, A., Gaugler, T., 2020. Calculation of external climate costs for food highlights inadequate pricing of animal products. Nat. Comm. 11, 6117. https://doi.org/10.1038/s41467-020-19474-6.

Quinn, J.C., Smith, T.G., Downes, C.M., Quinn, C., 2014. Microalgae to biofuels lifecycle assessment – multiple pathway evaluation. Algal Res. 4, 116–122. https://doi.org/10.1016/j.algal.2013.11.002.

Ramírez-Rodrigues, M.M., Estrada-Beristain, C., Metri-Ojeda, J., Pérez-Alva, A., Baigts-Allende, D., 2021. *Spirulina plantesis* protein as sustainable ingredient for nutritional food products development. Sustainability 13, 6849. https://doi.org/10.3390/su13126849.

RIVM, 2011. LCIA: The ReCiPe Model. Available online. https://www.rivm.nl/en/life-cycle-assessment-lca/recipe (14 December 2023).

Ropo, M., Mustonen, H., Knuutila, M., Luoranen, M., Kosonen, A., 2023. Considering emboided CO2 emissions and carbon compensation cost in life cycle cost optimization of carbon-neutral building energy systems. Environ. Impact Assess. Rev. 101, 107100 https://doi.org/10.1016/j.eiar.2023.107100.

Santos, A., Carvalho, A., Barbosa-Póvoa, A., 2022. A methodology for integrating the characterization factors uncertainty into life cycle assessments. Sustain. Prod. Consump. 33, 1018–1030. https://doi.org/10.1016/j.spc.2022.08.018.

Soni, R.A., Sudhakar, K., Rana, R.S., 2017. *Spirulina* – from growth to nutritional product: a review. Trends Food Sci. Technol. 69, 157–171. https://doi.org/10.1016/j.tifs.2017.09.010.

Tzachor, A., Smidt-Jensen, A., Ramel, A., Geirsdóttir, M., 2022. Environmental impacts of large-scale spirulina (*Arthrospira platensis*) production in Helsinki geothermal park Iceland: life cycle assessment. Mar. Biotechnol. 24, 991–1001. https://doi.org/10.1007/s10126-022-10162-8.

Van Fan, Y., Jaromír Klemes, J., Wan Alwi, S.R., 2021. The environmental footprint of renewable energy transition with increasing energy demand: eco-cost. Chem. Eng. Trans. 86, 204–499. https://doi.org/10.3303/CET2186034.

Vogelsang-O'Dwyer, M., Bez, J., Lykke Petersen, I., Skejovic Joehnke, M., Detzel, A., Busch, M., Krueger, M., Ispiryan, L., O'Mahony, J.A., Arendt, E.K., Zannini, E., 2020. Techno-functional, nutritional and environmental performance of protein isolates from blue lupin and white lupin. Foods 9, 230. https://doi.org/10.3390/foods9020230.

Wells, M.L., Potin, P., Craigie, J.S., Raven, J.A., Merchant, S.S., Helliwell, K.E., Smith, A. G., Camire, M.E., Brawley, S.H., 2017. Algae as nutritional and functional food sources: revisiting our understanding. J. Appl. Phycol. 29 (2), 949–982. https://doi.org/10.1007/s10811-016-0974-5.

Xia, Y., Yan, B., 2022. Energy-food nexus scarcity risk and the synergic impact of climate policy: a global production network perspective. Environ. Sci. Pol. 135, 26–35. https://doi.org/10.1016/j.envsci.2022.04.008.

Yang, Z., Xu, B., Liu, J., Zhan, J., Song, L., 2022. Dynamic changes of growth and physiological parameters of *Spirulina* cultivated outdoors – a case study in *Spirulina* industrial park in Inner Mongolia, China. J. Appl. Phycol. 34, 1163–1175. https://doi.org/10.1007/s10811-021-02680-0.

Ye, C., Mu, D., Horowitz, N., Xue, Z., Chen, J., Xue, M., Zhou, Y., Klutts, M., Zhou, W., 2018. Life cycle assessment of industrial scale production of *spirulina* tablets. Algal Res. 34, 154–163. https://doi.org/10.1016/j.algal.2018.07.013.

Zhang, M., Li, H., Chen, S., Liu, Y., Li, S., 2023. Interrogating greenhouse gas emissions of different dietary structures by using a new food equivalent incorporated in life cycle assessment method. Environ. Impact Assess. Rev. 103, 107212 https://doi.org/10.1016/j.eiar.2023.107212.

Zhen, H., Gao, W., Yuan, K., Ju, X., Qiao, Y., 2021. Internalizing externalities through net ecosystem service analysis – a case study of greenhouse vegetable farms in Beijing. Ecosyst. Serv. 50, 101323 https://doi.org/10.1016/j.ecoser.2021.101323.