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Comparative life cycle assessment of industrial and artisanal spirulina production systems

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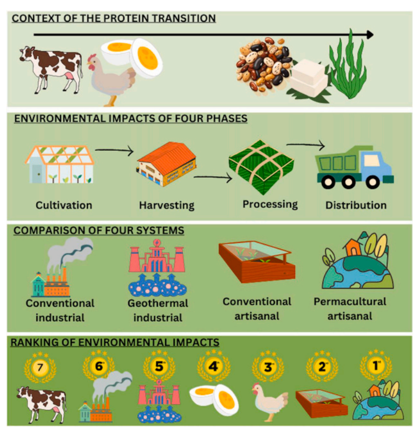
HIGHLIGHTS

- Spirulina emits up to 98 % less CO_2 than beef (4.56 vs. 187.17 kg CO_2-eq).
- Permacultural spirulina uses 73 % less land than the industrial system.
- Human toxicity drops by up to 77 % in permacultural vs. industrial spirulina.
- Permacultural spirulina ranks best on 6 of 8 indicators among spirulina systems.
- Spirulina's environmental performance varies greatly across production methods.

GRAPHICAL ABSTRACT



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ABSTRACT

Conventional food production, particularly animal protein, exerts considerable pressure on the environment. As part of the protein transition and global efforts towards sustainable agricultural practices, it is relevant to study low-impact protein alternatives and compare their environmental profiles with those of conventional animal sources.

This study examined spirulina, a protein-rich edible cyanobacterium. It compared the environmental impacts of four spirulina production systems (industrial, geothermal, artisanal and permacultural), with those of beef, poultry and eggs. The assessment used Life Cycle Assessment methodology, with a cradle-to-consumer scope and a functional unit of 1 kg of protein content.

The results showed that spirulina production, whatever the production system, has significantly lower environmental impacts than beef production, with up to 98 % lower greenhouse gas emissions (4.56 vs. 187.17 kg CO_2-eq) and over 99 % lower land use (0.25 vs. 116.95 m^2a crop eq). These benefits were less marked in comparison with poultry and eggs. Of the spirulina systems studied, the permacultural system performed best on five out of eight environmental indicators – including global warming, land use, and human toxicity – followed by the artisanal system, the geothermal system and, finally, the industrial system. Compared to the industrial

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system baseline, global warming impacts were reduced by 56–82 %, land use by 26–73 %, and human toxicity by up to 77 %, depending on the spirulina system. These results highlight the potential of spirulina as a promising alternative for the protein transition and the promotion of sustainable agricultural practices, particularly if produced in a permacultural way.

1. Introduction

Currently, food systems face a number of limitations. First, most of the agricultural activities are not sufficiently resilient to biotic, abiotic, economic and geopolitical stresses, which threaten the stability of food prices and the supply chain (Rabbi et al., 2023; Tzachor et al., 2021). Intensive livestock farming also increases the risk of the development of emerging diseases due to the high density of livestock – that may be immunocompromised due to poor living conditions – at the interface with humans (Magouras et al., 2020; Robin, 2021). Secondly, the major environmental impacts of our agricultural practices and their contribution to the crossing of planetary boundaries have already been well documented (Aiking, 2014; Akinnawo, 2023; Benton et al., 2021; Poore and Nemecek, 2018; Potapov et al., 2022; Munialo et al., 2022). Campbell et al. (Campbell et al., 2017) concluded that in 2017, of the five planetary boundaries located in a high-risk area (Steffen et al., 2015), agriculture was the main contributor to four of them – biogeochemical flows, freshwater use, land-system change, biosphere integrity, and contributed to the deterioration of the fifth – climate change. Meier (Meier, 2017) added that "*current agricultural and nutritional activities contribute […] to the transgression of three planetary boundaries: the loss of biodiversity, biogeochemical flows […], and land-system change*", and noted that it is the excessive use of nitrogen fertilisers that places the greatest pressure on these planetary boundaries. Third, food systems are struggling to meet the nutritional needs of the entire population in a fair way. Gerten et al. (Gerten et al., 2020) showed that if current agricultural activities were to remain within planetary boundaries, only 40 % of the world's estimated 8.2 billion inhabitants in 2025 (=3.4 billion) would have access to a balanced diet, including a sufficient supply of protein.

The main impact categories affected by agriculture are as follows. The food system contributes to climate change and ocean acidification through its high greenhouse gas (GHG) emissions, estimated by the IPCC to account for 21–37 % of global emissions (Munialo et al., 2022). Within this contribution, livestock is the most polluting agricultural sector, responsible for 18 % of global GHG emissions (Munialo et al., 2022), with beef production being the largest contributor (Poore and Nemecek, 2018). Agriculture also impacts freshwater depletion and water eutrophication, with this sector being responsible for 70 % of total freshwater withdrawals (FAO, 2011), as well as for 78 % of freshwater and ocean eutrophication (Poore and Nemecek, 2018) – mainly through the intensive use of nitrogen and phosphorus fertilisers, aquaculture effluents, and animal waste (Akinnawo, 2023). In addition, agriculture contributes to land-use change, with agricultural and livestock production now occupying half of all habitable land (Potapov et al., 2022). This trend is intensifying due to growing demand for food, biofuels, and other commodities driven by population growth and rising living standards (Potapov et al., 2022). Finally, agriculture contributes to biodiversity loss (Aiking, 2014; Benton et al., 2021) through habitat loss and fragmentation, as well as to air pollution via volatile organic compounds, sediment loss, soil erosion (Aiking, 2014; Benton et al., 2021) and the acceleration of nitrogen and phosphorus cycles through the use of fertilisers and manure (Aiking, 2014).

Animal proteins account for a third of global food protein consumption (FAO, 2022). The United Nations projections (United Nations, 2022) estimated that the global population will reach 9.7 billion in 2050, leading to an increase in food demand, including animal protein. In addition, the daily consumption of animal protein has increased by around 30 % in rich countries since the 1960s (Tzachor, 2019) and global demand for meat is expected to rise by 78 % between 2005 and 2050 (Alexandratos and Bruinsma, 2012). A similar increase is expected for other animal-based products (Fischer et al., 2014). The negative impacts of overproduction and overconsumption of animal proteins on the environment, human health and animal welfare have been widely documented (Springmann et al., 2018; Willett et al., 2019). In the absence of a shift in agricultural practices, population growth combined with rising demand for animal protein will lead to increased environmental pressures from agricultural activities. From these findings has emerged the idea of a protein transition, supported by the academic and decision-making spheres, as one aspect of the multi-stakeholder and cross-sectoral approach recommended to transform agricultural systems towards more sustainable, resilient practices that also improve food security (Willett et al., 2019; European Commission, 2020a; Le Mouël et al., 2016). This concept, although its definition and the metanarratives that constitute it are not uniform (Duluins and Baret, 2024; Katz-Rosene et al., 2023), can be defined as the gradual rebalancing between animal and plant proteins, involving a partial substitution of animal proteins with alternatives (Duluins and Baret, 2024). It aims at reducing the share of animal protein (produced and consumed) in dietary protein intake with a parallel increase in protein alternatives. The ultimate goals include (i) reducing the environmental impact of protein production and consumption and therefore the total impact of agricultural activities, (ii) providing a high-quality food supply to a growing population, and (iii) reducing the health and animal welfare problems associated with intensive livestock farming (Tzachor et al., 2021; Duluins and Baret, 2024).

In the context of the protein transition, several protein alternatives have been suggested, including legumes, microalgae (e.g. spirulina, chlorella), macroalgae, mycoproteins, insects, hemp and in vitro meat (Tzachor et al., 2021; European Commission, 2022; Shen et al., 2021). The advantages of these food sources are the reduced exposure to biotic and abiotic stresses of their production, their adaptability to different geographical areas, which promotes both supply risk-resilience – defined here as a supply that is "*consistent in the provision of essential macro- and micronutrients in the face of disturbances*" (Tzachor et al., 2021), and their low environmental impact. It is essential to assess the reduction in environmental impacts brought about by these protein sources compared with those generated by conventional sources of animal protein in order to identify the environmental potential of each protein alternative. Indeed, as emphasised by Duluins & Baret (Duluins and Baret, 2024), it is vital to assess whether the proposed alternatives meet the three goals of the protein transition. Although the protein transition also has other aims than reducing the environmental impacts, in this study, we confined ourselves to analysing environmental impacts of one alternative, as not meeting this aim would already strongly constrain its further development as a sustainable source of protein.

This study focused on spirulina, an edible microalga, because it stands out from other alternatives in several respects. Not only does it have a high nutritional density and a well-balanced essential amino acids profile for human consumption, but it can also be grown on non-arable land (FAO, 2008). It requires up to 5 times less water than conventional irrigated crops (Fox, 1999) and has a high protein yield (spirulina grows up to 10 times faster than terrestrial plants (Keil et al., 2023)). With ~60 % of its dry weight in protein, the quantity of protein produced per unit area is on average 40 times greater than that of soy and 200 times greater than that of beef (FAO, 2008). The development of algae farming is also encouraged in Europe by the Green Deal's 'From Farm to Fork' strategy: '*[The European Maritime and Fisheries Fund] will also set out well-targeted support for the algae industry, as algae should* *become an important source of alternative protein for a sustainable food system and global food security*' (European Commission, 2020b).

This study was aligned with the existing literature, which has proposed three Life Cycle Assessments (LCA) conducted on whole spirulina production systems for human food consumption, namely those of Ye et al. (Ye et al., 2018), investigating an industrial system in China, Tzachor et al. (Tzachor et al., 2022a; Tzachor et al., 2022b), investigating a geothermal system in Iceland, and Fernández-Ríos et al. (Fernández-Ríos et al., 2024), examining artisanal systems in Spain. Other studies have examined either food- or non-food uses of spirulina derivatives (e.g. phycocyanin, biogas) (Papadaki et al., 2017; Rodríguez et al., 2018), or theoretical models of spirulina production (Quintero et al., 2021).

The study by Ye et al. (Ye et al., 2018) concluded that the production of 1 kg of spirulina tablets in the system studied mainly impacted the following environmental categories: global warming (7.7 kg CO_2 eq.), smog (0.44 kg O_3 eq.), acidification (0.096 kg SO_2 eq.), eutrophication (0.022 kg N eq.), and fossil fuel depletion (12.7 MJ surplus). Per kilogram of protein produced, spirulina tablets had a better environmental profile than milk in 9 out of 10 impact categories (Ye et al., 2018), and a comparable profile to tofu, with similar results in 5 out of 10 impact categories, and the remaining ones favouring either tofu or spirulina depending on the category (Ye et al., 2018). The study by Tzachor et al. (Tzachor et al., 2022a; Tzachor et al., 2022b) concluded that producing 1 kg of wet spirulina biomass in Hellisheiði geothermal park required 0.0378 m^2 of land and 8.360 m^3 of freshwater, whereas producing 1 kg of beef required 361.21 m^2 of land and 1451 m^3 of freshwater. The study also concluded that producing spirulina in the photobioreactor facility at the Hellisheiði geothermal park was carbon-neutral (Tzachor et al., 2022b). Finally, the study by Fernández-Ríos et al. (Fernández-Ríos et al., 2024) showed that producing 1 kg of spirulina in an artisanal system generated half the GHG emissions of the industrial system studied by Ye et al. (Ye et al., 2018; Fernández-Ríos et al., 2024). The analysis also concluded that more than 80 % of GHG emissions came from the cultivation phase (Fernández-Ríos et al., 2024), as was also the case in the study by Ye et al. (Ye et al., 2018).

However, three major gaps remained in the litterature, which were addressed in our study, making it innovative. First, the literature lacked any comparison between different spirulina production systems. Given that significant differences in environmental impact are likely to exist between different production methods (Fernández-Ríos et al., 2024), it was relevant to assess how spirulina, produced in various ways, compared to conventional protein sources. Our comparison offered valuable insights into the potential integration of spirulina into sustainable food systems. The second gap was that the only available data on artisanal production systems were found in the recent study by Fernández-Ríos et al. (Fernández-Ríos et al., 2024), whereas artisanal spirulina systems are widespread in Europe, with more than 447 artisanal algae and spirulina plants across the continent (Araújo et al., 2020). The demand for spirulina increased by approximately 8.7 % in Europe between 2022 and 2025, and this growth is expected to continue (Seaweed as a Growth Engine for a Sustainable European Future, 2020). The European Union is one of the world's main importers of seaweed products (€554 million recorded in 2016 (Fernández-Ríos et al., 2024)) and most of the production takes place in Asia, especially in China (the size of the Chinese spirulina market was estimated at 67.2 million USD in 2023 (Sili et al., 2012)). Thus, studying European production systems contributed to supporting a sustainable European spirulina sector (Fernández-Ríos et al., 2024). The third gap was that two of the three existing LCAs (Ye et al., 2018; Tzachor et al., 2022a; Tzachor et al., 2022b) were limited to cradle-to-gate impacts, excluding the distribution phase to the consumer. However, the majority of spirulina production takes place in Asia (Sili et al., 2012), which requires long-distance transport to reach European consumers. Consequently, it was relevant to include the distribution phase in the quantification of impacts.

2. Materials and methods

2.1. Goal and scope

Using a comparative analysis and a LCA methodology, the study aimed to answer three main goals, namely (i) assess the environmental potential of spirulina as a protein alternative in the food transition, (ii) quantify and compare the environmental impacts of four spirulina production systems, namely industrial (S_INDU), geothermal (S_GEO), artisanal (S_ART) and permacultural (S_PERMA), in order to determine the variations in environmental impacts between different production methods, and (iii) compare the impacts with those of three reference systems: beef (BEEF), poultry (POUL), and eggs (EGG).

These reference systems were primarily chosen to offer a variety of points of comparison with a wide range of environmental impacts: beef is known to have a high impact, while poultry and eggs have an intermediate impact between animal proteins and plant alternatives (De Vries and de Boer, 2010). As for chicken, it is the second most important source of protein consumed worldwide in terms of mass (Statista, 2023). With regard to eggs, the production model for this product is different from that used for meat (the animal is not slaughtered) and therefore offered a reference system that also took account of the ethical and animal welfare issues involved in the livestock farming debate (provided that the farming conditions are respectful). Furthermore, although dairy products are more widely consumed than eggs worldwide (Statista, 2023), in terms of weight, eggs were chosen for three main reasons. First, their amino acids profile is closer to that of spirulina (Ciqual Anses (s.d.), n.d.). Second, spirulina and eggs both contain pigments that play a powerful antioxidant role in the human body (FAO, 2008; Ruxton et al., 2010), which dairy products do not contain. Third, lactose intolerance affects around 60 % of adults (Catanzaro et al., 2021), limiting the consumption of this source of protein. Moreover, it was relevant to compare spirulina with animal proteins rather than plant proteins, as its amino acid profile is more similar to that of animal-based sources (FAO, 2008; Ciqual Anses (s.d.), n.d.).

The assessment was carried out using a cradle-to-consumer approach, with ReCiPe 2016 as the impact assessment methodology and 1 kg of protein as the functional unit. We followed the ISO 14040 and ISO 14044:2006 standards. While this study was primarily descriptive in scope, other future applications are possible. The results along with the Life Cycle Inventory (LCI) data can serve as a foundation for future decision-support studies and contribute to structural changes at the meso or macro level in national or international food systems. Accordingly, attributional modelling – which represents a system in isolation from the rest of the technosphere – was selected (Dijkman et al., 2018).

2.1.1. Functional unit

The functional unit chosen was 1 kg of protein content, as the study focused on spirulina as a protein source. As the four cultivation methods resulted in different finished products, their protein content varied. The industrial system (S_INDU) resulted in spirulina tablets containing 80 % dry spirulina (protein content: 50 %, so 2 kg of tablets were needed to obtain 1 kg of protein). The geothermal system (S_GEO) and the artisanal system (S_ART) produced dry spirulina powder or twigs (protein content: 60 %, so 1.7 kg of powder were needed to obtain 1 kg of protein). The permacultural system (S_PERMA) produced fresh spirulina (protein content: 30 %, so 3.3 kg of fresh spirulina were required to obtain 1 kg of protein). With regard to the reference systems, BEEF and POUL produced fresh beef meat and chicken meat, respectively (protein content: 20 %, so 5 kg of meat were needed to obtain 1 kg of protein). EGG produced fresh eggs (protein content: 12 %, so 8.33 kg of eggs were needed to obtain 1 kg of protein). To ensure a consistent comparison of the quantities of protein supplied, the functional unit equalised the finished products according to their protein content.

2.1.2. Reference systems

As this analysis was a comparative one, each system was evaluated in relation to the other three. In addition, the results were compared with three external reference systems, all located in the Netherlands and whose products were transported by refrigerated trucks to Brussels: (i) conventional beef production (BEEF), (ii) conventional poultry production (POUL) and (iii) conventional egg production (EGG). These reference systems were modelled in SimaPro software, using background data from the Agri-footprint and EcoInvent databases. For more details on their modelling and calculations, the reader is invited to consult Supplementary Data Tables A–C.

The choice of these three reference systems was based on the presence of significant differences in environmental impact between different sources of animal protein. Beef is known to have the greatest impact, while poultry and egg production have a lower impact (De Vries and de Boer, 2010). However, it should be noted that there are also variations in impacts between different production systems for the same protein source, and these were not captured by the analysis.

2.1.3. Representativeness of LCI data

The collection of foreground data relating to spirulina production was done via two channels. Those for S_INDU and S_GEO came from the literature (Ye et al., 2018; Tzachor et al., 2022a; Tzachor et al., 2022b), while those for S_ART and S_PERMA were collected directly at the Spirulinerie of Gaume (Belgium) in June 2024 and at The Roquette Farm (Occitanie region, France) in July 2024, respectively. These data had to be considered in their geographical, temporal and technological context to ensure their representativeness. Indeed, the systems were located in different countries with different climates. In addition, the data represented the four systems as they were conducted at a given time (data collected in 2018 for system S_INDU, 2022 for system S_GEO, 2024 for systems S_ART and S_PERMA). It is possible that technological or agronomic developments have occurred since the data were collected; however, any such changes were not included in the present study. The background data came from the EcoInvent (EcoInvent, 2020) and Agri-footprint (Agri-footprint, 2021) databases.

2.1.4. Allocations

In terms of outputs, only S_INDU generated a co-product: a spirulina residue used as animal feed. This residue was treated by allocation through extension of the system boundaries and substitution: the environmental impacts of an equal mass of conventional animal feed was subtracted from those of S_INDU. Allocation by mass was justified because this residue has nutritional qualities comparable per unit mass to conventional animal feed. The inputs to be allocated were divided into two categories.

Family A included inputs that would have been underused if they had not been valued by the spirulina cultivation system. The environmental impacts of these inputs were not allocated to spirulina cultivation, because (i) their non-use would not have harmed the environment and (ii) this maintained equivalent methodological considerations with (Tzachor et al., 2022a; Tzachor et al., 2022b) from which the data for S_GEO were derived. In S_GEO, the cold and warm water flows from the Hellisheiði geothermal park belonged to family A. In S_PERMA, the seaweed from Brittany contained in the macerate of seaweed dissolved in sulphuric acid was classified in family A, as it would have remained underused without polluting Brittany's waters if it had not been used as a nitrogen fertiliser.

Family B included inputs that would have generated environmental impacts if they had not been recycled by the spirulina system. The impacts associated with their treatment as waste were subtracted from the spirulina system, thereby providing an environmental credit. In S_PERMA, ammonium sulphate from Breton pig manure fell into this category. Had it not been used in this spirulina system, the manure would have polluted the soil and waterways of Brittany, where it is found in excess, due to the intensive livestock farming carried out in this region (Durand, 2021; Nitrates dans les cours d'eau bretons : analyse de l'évolution annuelle depuis 1995, n.d.) and would therefore have had to be treated as waste.

2.1.5. Systems boundaries

Taking a cradle-to-consumer approach, the study covered four life cycle phases: cultivation, harvesting, processing and distribution (Fig. 1). Previous LCAs typically focused on a cradle-to-gate scope, however, our study also evaluated the distribution phase, as we compared systems located across different continents that were intended for a European consumer. With regard to the distribution phase, a number of assumptions were made. First, the journey was made from the production site to the final consumer (Brussels, Belgium), without passing through intermediate warehouses. Second, the modes of transport considered were those most commonly used to transport dry food products over the distances studied. Finally, the quantity transported in one journey corresponded to the amount of finished product equivalent to 1 kg of protein (the functional unit).

2.1.6. Foundations of the impact assessment

Environmental impacts were computed using SimaPro software (PRé Sustainability, 2024). We used the ReCiPe 2016 methodology (hierarchical cultural perspective, V1.09), applicable on a global scale. In order to limit the uncertainties associated with the endpoint indicators, we focused most of the analysis on the midpoint indicators to assess the impacts of the seven systems. Given the scope and objectives of the study, we chose to study eight midpoint impact categories, the most commonly considered in LCAs of food products: particulate matter, human toxicity (cancer and non-cancer), terrestrial ecotoxicity, global warming, water use, freshwater eutrophication and land use. These indicators provided a sufficiently broad coverage of the main environmental issues associated with food production, and the data available allowed a robust quantification of these categories. Furthermore, five of these indicators were included in the SQUIID indicator (Simplified Quantitative Impact Indicator for food Dishes), which encompasses the environmental impact categories with the most significant contribution to the single score (i.e. global warming potential (GWP), particulate matter formation, land occupation, human non-carcinogenic toxicity and water consumption) (Arfelli et al., 2024). Human carcinogenic toxicity and terrestrial ecotoxicity were added because the findings in (Ye et al., 2018) showed that both impact categories were highly impacted.

For the comparative analysis of certain processes (i.e. fertilisers and modes of transport) and production phases (i.e. cultivation and distribution), we used the three ReCiPe 2016 endpoint indicators (i.e. human health, ecosystems, resources), as the large number of processes compared made it irrelevant to consider eight midpoint indicators.

2.1.7. Methodological limitations

Firstly, infrastructure and direct land use were excluded due to the lack of data for certain systems – namely S_INDU, and S_GEO. However, as far as land use was concerned, indirect land use was considered sufficient to accurately represent the land use indicator, as the direct production area of the two systems for which data were available was very small compared to their indirect land use. This observation supported the assumption that direct land use was likely negligible across all systems. It was essential to consider not only the surface area of land occupied, but also the nature of the land farmed (e.g. arable or not) and the land use management practices put in place by the producer (e.g. planting local species to promote biodiversity or, on the contrary, leaving land bare). As these aspects are not included in the land use indicator, a qualitative interpretation was proposed, based on scientific literature and field observations.

Secondly, with regard to the water consumption indicator, the systems had different water renewal practices: some systems renewed all the water in the growing basins each year, while others retained the

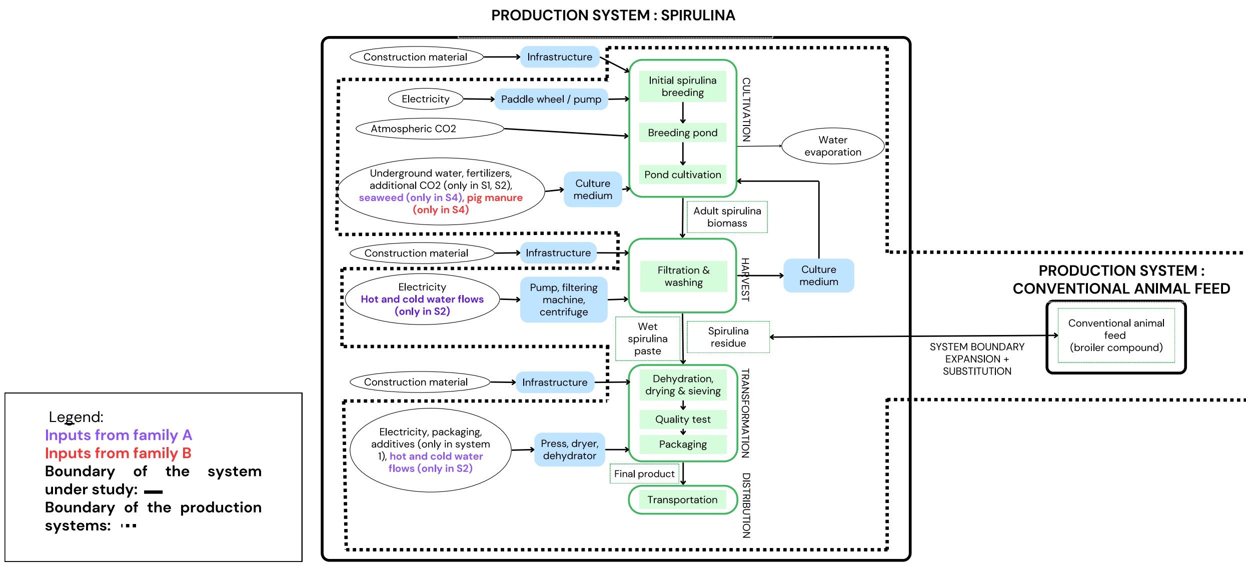

Fig. 1. General flow chart for spirulina production systems.

same water from year to year. To ensure a fair comparison, we applied a water amortisation method over a 10-year period. For systems that never renewed water, the initial water input was divided by 10 to reflect annualised consumption (S_PERMA was confirmed to retain water from year to year, while for S_INDU and S_GEO, it was uncertain, but based on the information provided in (Ye et al., 2018; Tzachor et al., 2022a; Tzachor et al., 2022b), it was reasonable to assume they did too). Systems that renewed water yearly were fully accounted for each year (S_ART). This approach avoided bias in water retention in systems over the long term. Amortisation is a recognized approach in LCA for handling capital goods (i.e., "*physical assets used in the manufacturing of products that outlive their production process*" (Agez et al., 2022)) (Mahlan et al., 2025). While previous studies applying water amortisation in spirulina cultivation systems were unavailable – likely due to the novelty of comparing multiple spirulina production methods – this method aligned with established LCA practices (Mahlan et al., 2025). Thus, applying water amortisation ensured that water use impacts were neither overestimated in systems that retained water over time, nor underestimated in those with annual renewal.

Thirdly, with regard to the reference systems, we bore in mind that different production methods for the same type of animal protein do not have the same impacts (e.g. organic local beef farming vs. conventional intensive long-distance beef farming). However, our study did not reflect this diversity, and was limited to a model of European beef, poultry and egg production, based on data from the Agri-footprint database (which is derived from a broad range of Dutch scenarios).

2.2. Life cycle inventory

S_INDU and S_GEO were described respectively in (Ye et al., 2018; Tzachor et al., 2022a; Tzachor et al., 2022b) and, in the present study, were not described beyond Table 1 setting out their main characteristics. On the other hand, S_ART and S_PERMA were described beyond Table 1, as they were based on new data collected from producers. S_PERMA was described in greater depth, as it was an innovative permacultural system. The characteristics of the four systems were summarized in Table 1, their material and energy flows for the functional unit in Table 2, and a graphical representation of the flows, general to the four systems, in Fig. 1. For further details on calculation, and data used in SimaPro, see Supplementary Data Tables D–G.

2.2.1. Systems description

2.2.1.1. S_ART – artisanal system. This system was an artisanal, off-ground raceway pond culture, in a greenhouse with neither artificial heating nor lighting, and with no additional CO_2 flow. Cultivation took place in four basins totalling 500 m^2 of floor space and 115 m^3 of culture medium. Each tank was equipped with a paddle wheel powered by an electric motor, which operated 6 h a day during the growing months (May to September). The growing medium was maintained at a pH of around 10.5.

At the start of each season, the producer bred new strains, which were then placed in the basins. Once the 115 m^3 volume was reached, the harvesting phase began, and five days a week, around 2 kg of fresh spirulina were harvested. During harvesting, part of the culture medium was pumped out, then the biomass was hand-filtered and transferred to the press. The excess water was returned to the basins. Thanks to this closed circuit, no water was lost except through evaporation. The result of this stage was a mass of fresh spirulina. Next, the processing phase began, during which the mass of spirulina was transferred to a pusher (a tool where biomass is inserted and, by pushing a lever, shaped into filaments through small holes) that formed fine twigs. These twigs were placed on dehydrator trays and then dehydrated at 60 °C for 2 h. This stage produced a finished product: dry spirulina twigs packaged in kraft paper bags. At the end of the season, the 115 m^3 of culture medium were removed and the basins were cleaned of the deposits of nutrients and dead spirulina that had fallen to the plastic liner at the bottom of the basins. This represented a significant difference from the permacultural system, in which the culture medium remained in place from year to year, thus considerably reducing water consumption. The electricity used for growing activities was taken from the grid, supplied by a 100 % Belgian renewable energy provider, mainly sourced from wind and solar power. Eventually, solar panels will be installed on site.

2.2.1.2. S_PERMA – permacultural system. The domain in which the spirulina production plant was located was home to many local species of trees, making it a biodiversity sink (Planchon, 2022). The greenhouse, covering an area of 300 m^2, housed 150 m^2 of basins for a total of 15 m^3 of growing medium, with an average pH of 10.4. The basins were continuously stirred by six electric pumps. No heating, artificial lighting, or additional flow of CO_2 was used. CO_2 biofixation relied solely on atmospheric CO_2, as in S_ART and unlike S_INDU and S_GEO, which used additional bottled CO_2. The original strain, which originated in the

Table 1
Summary of the characteristics of spirulina production systems.

	S_INDU	S_GEO	S_ART	S_PERMA
Location	Beihai (China)	Hengill (Island)	Tintigny (Belgium)	Tourbes (France)
Data collection	Literature: Ye et al. (2018)	Literature: Tzachor et al. (2022a, 2022b)	Collected in the field	Collected in the field
Cultivation system	Raceway ponds (open, off-ground system)	Closed (PBRs flat-panel)	Raceway ponds (open, off-ground system)	Open (basins in contact with the soil)
Farm size	Big	Medium	Small	Small
Annual production	240 t	60 t	500 kg	280 kg
Artificial heating and lighting	Absent	Present	Absent	Absent
Greenhouse	Absent	Absent	Present	Present
Water consumption	Water maintained in the cultivation basins from season to season. Losses through evaporation (because the system is open)	Water maintained in the cultivation basins from season to season. No water loss (because the PBR system is closed)	Renewal of the water in the cultivation basins each new season. Losses through evaporation (because the system is open)	Water maintained in the cultivation basins from season to season. Losses through evaporation (because the system is open)
Origin of fertilisers	Synthetic	Synthetic + of natural origin (mines)	Synthetic + of natural origin (mines)	Of natural origin (algae, manure and mines)
Reasoned use of fertilisers	No	No	No	Yes
Addition of an artificial CO_2 flow	Yes	Yes	No	No
Origin of energy	Country's conventional energy mix + biomass	Geothermal	Renewable	Renewable
Finished product	Tablets (80 % dry spirulina; 50 % protein)	Powder (100 % dry spirulina; 60 % protein)	Twigs (100 % dry spirulina; 60 % protein)	Fresh biomass (100 % fresh spirulina; 30 % protein)
Cultivation period	All year round (12 months/year)	All year round (12 months/year)	May–September (5 months/year)	May–October (6 months/year)
Rich biodiversity on the production site	Non-existent	Non-existent	Non-existent	High

Camargue (a natural region in the south of France), had gradually adapted to the climatic and edaphic conditions at The Roquette Farm, giving rise to four distinct strains, which were growing in the basins at the time of data collection.

Cultivation followed the principles of permaculture, defined as '*consciously designed landscapes which mimic the patterns and relationships found in nature, while yielding an abundance of food, fibre and energy for provision of local needs*' (Holmgren, 2002). The culture mimicked the development of spirulina in its natural living environment, i.e. saline and alkaline lakes, which is why the culture could be described as a mesocosm.[1] The system was based on basins in contact with the soil, unlike the other systems, which were grown off the soil (either PBR or raceway pond). The growing medium circulated between several basins, of which there were two types: (i) two rectangular basins of 60 m^2 each, 10 cm deep (12 m^3 of growing medium), favouring intense photosynthesis and high productivity, and (ii) a circular basin of 30 m^2, 2 m deep but only 10 cm full (3 m^3 of growing medium). The high edges of this deep basin provided shade, creating a resting area that, although not particularly productive, was essential for preserving the strain's longevity.

In lakes where spirulina grows naturally, nutrients come from the soil. To reproduce this process, a substrate made of clay, sand and organic matter lined the bottom of the basins. This direct contact with the soil offered several advantages for the resilience of this system (i.e. resilience is here defined as the capacity of a system to deal with change and continue to develop). Firstly, thanks to its buffering properties, clay acted as a nutrient reservoir, capturing excess nutrients and releasing them when necessary, thereby reducing the need for fertilisers. Secondly, clay provided a refuge for spirulina in the event of environmental stress (e.g. excessive heat, pH imbalance, increased salinity). Thirdly, dead spirulina decomposed naturally in the substrate, contributing to a self-sustaining nutrient cycle. Lastly, unlike other systems, there was no need to clean the tanks at the end of the season or renew the culture medium (which would have meant growing a young strain and filling the basins with a new culture medium). The medium remained in place year after year and spirulina was dormant in winter. The system was self-purifying and self-regenerating thanks to the clay substrate.

The low frequency of harvesting, carried out three times a week from May to October, helped to preserve the vigour of the strain and was recommended in this system where strains were kept year after year. At each harvest, 100 L of culture medium were pumped out, hand-filtered and then centrifuged. Excess water was re-injected into the basins. Each harvest yielded around 4 kg of fresh spirulina biomass, packaged in plastic film.

The permacultural approach favoured locally produced fertilisers. Following observation of the bacterial methanisation that occurs naturally in the natural lakes where spirulina grows (Fox, 1999), the producer obtained nitrogen from a system of biomethanisation and stripping of Breton pig manure. This two-stage process first transformed the manure into digestate rich in ammoniacal nitrogen and organic matter. As the organic matter content of this digestate was too high for spirulina, 80 % of the ammoniacal nitrogen was extracted by stripping, then recovered in the liquid phase by dissolution in an aqueous ammonium sulphate solution stabilised by 10 % sulphuric acid (Palakodeti et al., 2021). Furthermore, phosphoric acid was obtained from Breton seaweed macerated in sulphuric acid. Magnesium sulphate and potassium sulphate came from French and German mines. Finally, the trace elements and chelated iron were purchased from French producers.

A particular feature of this growing system was the reasoned use of fertilisers. Rather than adding fertilisers according to theoretical calculations based on the harvested spirulina biomass, the farmer performed a weekly analysis of the culture medium and adjusted the inputs accordingly, which were often lower than the theoretical inputs. As far as water use was concerned, the farm followed the permacultural principle of water autonomy. The water in the basins, which came from a well, had been in place since the first year of cultivation and had not been renewed. In the event of an imbalance in the composition of the culture medium, the water was recycled to recreate a stable culture medium, thus avoiding any losses. The discharged water was purified by plant

[1] **Mesocosm**: '*A mesocosm [is] defined by Odum as a bounded and partially enclosed outdoor experimental unit that closely simulates the natural environment, particularly the aquatic environment*' (Crossland and La Point, 1992).

Table 2
Inventory data for the functional unit for spirulina production systems.

Phase		Data	S_INDU	S_GEO	S_ART	S_PERMA
Cultivation	Inputs	Basins water (underground)	1290.4 L	0.041 L	391 L	17.8 L
		Evaporation compensation (underground)	238 L		102 L	63.66 L
		Electricity from the grid (>60 % fossil)	4 kWh			
		Geothermal electricity		231.20 kWh		
		Renewable electricity			4.90 kWh	0.61 kWh
		Urea ($(NH_2)_2CO$)	1.26 kg			
		Sodium nitrate ($NaNO_3$)	0.60 kg	0.75 kg		
		Sodium chloride (NaCl)	0.34 kg		2 kg	0.53 kg
		Potassium chloride (KCl)	0.34 kg			
		Potassium nitrate (KNO_3)			0.78 kg	
		Potassium sulfate (K_2SO_4)				0.03 kg
		Magnesium sulfate ($MgSO_4$)				0.03 kg
		Iron sulfate ($FeSO_4$)	0.08 kg	0.27 kg	0.02 kg	
		Iron chelate EDTA				0.03 kg
		Monoammonium phosphate ($NH_4H_2PO_4$)	0.18 kg		0.09 kg	
		Dipotassium phosphate (K_2HPO_4)		2.14 kg		
		Sodium bicarbonate ($NaHCO_3$)	4.20 kg		3.90 kg	1.42 kg
		Ammonium sulphate from manure (NH_4SO_4)				1 L
						6.6 kg
		- Pig manure (deducted; allocation "input of family B")				0.1 L
		- Sulphuric acid (accounted for) (10 %)				
		Phosophoric acid from algae (H_3PO_4)				0.03 L
						/
		- Algae (unaccounted for; allocation "input of family A")				0 L
		- Sulphuric acid (accounted for) (10 %)				
		Food-grade CO_2	0.75 kg			
	Outputs	CO_2 absorption by biofixation	−3 kg	−3 kg	−3 kg	−3 kg
		Water loss through evaporation	238 L		102 L	63.66 L
Harvesting	Inputs	Electricity from the grid (>60 % fossil)	6.40 kWh			
		Geothermal electricity		5.95 kWh		
		Water	214 L			
		Renewable electricity			1.16 kWh	1.20 kWh
	Outputs	CO_2 emitted by fossil fuel	2.82 kg			
		Spirulina residue used as animal feed	0.04 kg			
Processing	Inputs	Electricity from the grid (>60 % fossil)	1.12 kWh			
		Geothermal electricity		0.34 kWh		
		Renewable electricity			2.68 kWh	6.80 kWh
		Cellulose microcristalline	0.20 kg			
		Colloidal silicon dioxide	0.10 kg			
		Sodium carboxymethyl cellulose	0.10 kg			
		Kraft paper packaging			0.05 kg	
		Plastic film packaging	0.05 kg	0.05 kg		0.09 kg
Distribution	Outputs	Truck	0.184 tkm	0.15 tkm	0.29 tkm	
		Refrigerated truck				3.53 tkm
		Ship	35.77 tkm	4.68 tkm		

purification on site, before being reused to irrigate the domain's vegetable patches. A 50 m^3 tank stored rainwater collected on the greenhouse roof. The electricity required for production was provided by a solar energy supplier.

2.3. Impact assessment

2.3.1. General comparison of the systems

Table 3 shows the midpoint indicator data for the 7 systems studied: the orange and green cells highlight the most and least harmful system for each indicator, respectively. S_PERMA recorded the highest scores for 5 out of 8 indicators per kg of protein produced: global warming (4.56 kg CO_2 eq), fine particles matter formation (0.01 kg $PM_{2.5}$ eq), freshwater eutrophication (0.01 kg P eq), human toxicity (non-carcinogenic) (5.85 kg 1.4 DCB) and land use (0.25 m^2a crop area). Conversely, BEEF scored worst for 6 of the 8 indicators studied: global warming, fine particles, freshwater eutrophication, human toxicity (non-carcinogenic), land use and water consumption. The radar plot (Fig. 2) summarized the differences between the environmental performances of S_PERMA (orange) and BEEF (blue). The differences were significant for all indicators except for human carcinogenic toxicity and terrestrial ecotoxicity.

A multi-criteria analysis (D-Sight, 2025) assigning equal weight to each indicator showed that permacultural spirulina had the best environmental potential, followed by poultry meat production, then artisanal spirulina, then eggs, then geothermal spirulina, then industrial spirulina, then beef (Fig. 3).

A comparison of the four spirulina production systems showed a downward trend, with S_INDU having the highest impact, then S_GEO, then S_ART, and finally S_PERMA, which had the lowest. The environmental performances of S_INDU (blue), S_GEO (black), S_ART (green), and S_PERMA (orange) were summarized in the radar plot (Fig. 4). Taking S_INDU system as a baseline, the global warming impacts were reduced by 56 % in S_GEO, 77 % in S_ART, and 82 % in S_PERMA. Similarly, fine particulate matter formation decreased by 75 % in all three systems, compared to S_INDU. Land use impacts dropped by 26 % (S_GEO), 40 % (S_ART), and 73 % (S_PERMA). In terms of human non-carcinogenic toxicity, S_GEO and S_ART showed reductions of 44 % and 46 %, respectively, while S_PERMA achieved the highest reduction (77 %). Conversely, S_GEO showed substantially higher terrestrial ecotoxicity (+367 %) and human carcinogenic toxicity (+220 %) than S_INDU, whereas S_ART and S_PERMA reduced these categories by 53 % and 65 %, respectively. Water consumption varied moderately, with S_ART increasing by 31 %, while S_GEO and S_PERMA reduced it by 13 % and 20 %, respectively. No differences were observed in freshwater eutrophication among the four systems.

Table 3
Comparison of systems (all phased considered) – midpoint indicators.

Impact category	Unit	S_INDU	S_GEO	S_ART	S_PERMA	BEEF	POUL	EGG
Global warming	kg CO_2.eq	25.53	11.12	5.93	4.56	187.17	18.01	22.17
Fine particulate matter formation	kg $PM_{2.5}$-eq	0.04	0.01	0.01	0.01	0.61	0.10	0.16
Freshwater eutrophication	kg P-eq	0.01	0.01	0.01	0.01	0.03	0.01	0.01
Terrestrial ecotoxicity	kg 1.4-DCB	165.52	772.24	97.36	77.61	124.58	33.24	48.77
Human carcinogenic toxicity	kg 1.4-DCB	3.64	11.68	2.37	1.28	1.00	0.20	0.26
Human non-carcinogenic toxicity	kg 1.4-DCB	25.05	13.92	13.58	5.85	129.23	22.76	25.05
Land use	m^2a crop eq	0.92	0.68	0.55	0.25	116.95	26.26	37.10
Water consumption	m^3	0.54	0.47	0.71	0.43	1.02	0.21	0.44

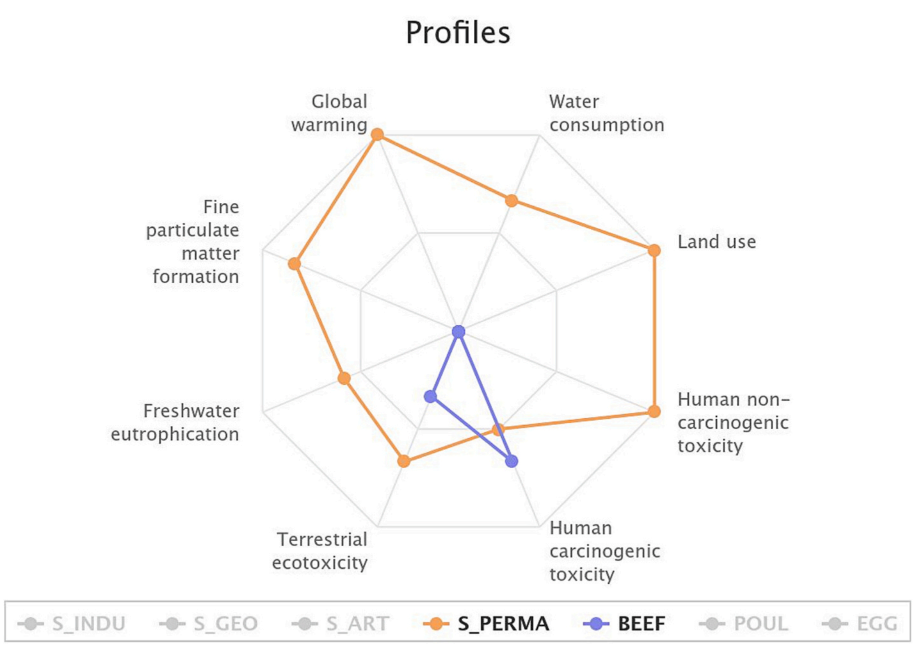

Fig. 2. Radar plot comparing the environmental performance of S_PERMA and BEEF across all midpoint indicators (D-Sight, 2025).

Among the four spirulina systems, S_INDU had the highest environmental impact for 6 out of 8 indicators per kg of protein: global warming (25.53 kg CO_2 eq), fine particles matter formation (0.04 kg $PM_{2.5}$ eq), human toxicity (non-carcinogenic (25.05 kg 1.4-DCB) and carcinogenic (3.64 kg 1.4-DCB)), land use (0.92 m^2a crop area) and water consumption (0.54 m^3). The only indicators where S_INDU was not the most harmful were freshwater eutrophication (the four systems had an equivalent impact) and terrestrial ecotoxicity. For the latter, it was S_GEO that had the highest impact, with the cultivation phase contributing to more than 97 % of this impact. This impact was mainly due to the supply of geothermal electricity (>95 % of the impact of the cultivation phase) and, based on available litterature, could be explained by two main factors. On the one hand, the impact was due to pollution from geothermal fluids. More than 90 % of the impact of this electricity was linked to zinc, brought to the surface by geothermal fluids pumped into the reservoir (IEA, 2010). These fluids often contained heavy metals which, if poorly managed, could pollute soil and groundwater (IEA, 2010; Papakostas et al., 2022). In addition, (Paulillo et al., 2019) highlighted that the steel and copper used for the geothermal wells and the cogeneration plant were among the main contributors to freshwater ecotoxicity in the Hellisheiði geothermal plant. On the other hand, the magnitude of the impact of geothermal electricity in S_GEO was explained by high energy consumption, as the cultivation phase of S_GEO required a considerable amount of energy to power the lighting and stirring devices essential for spirulina growth in an environment that was not conducive to photosynthesis (Iceland). The high amount of electricity might also have been due to the technology (i.e. PBR), which was different from the open basins used in the three other systems. In

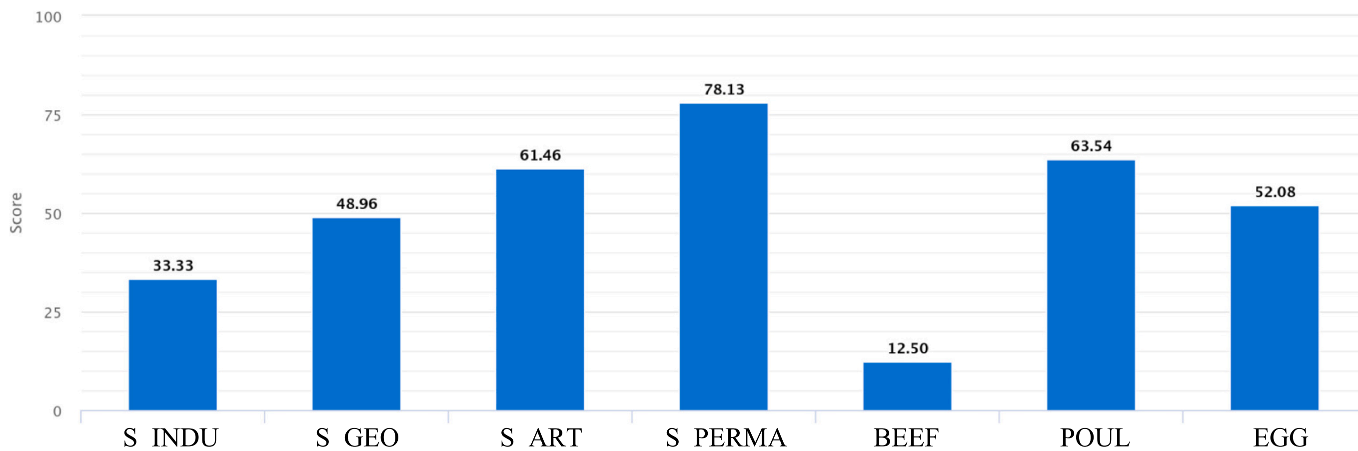

Fig. 3. Multi-criteria analysis of midpoint indicators of all systems (D-Sight, 2025).

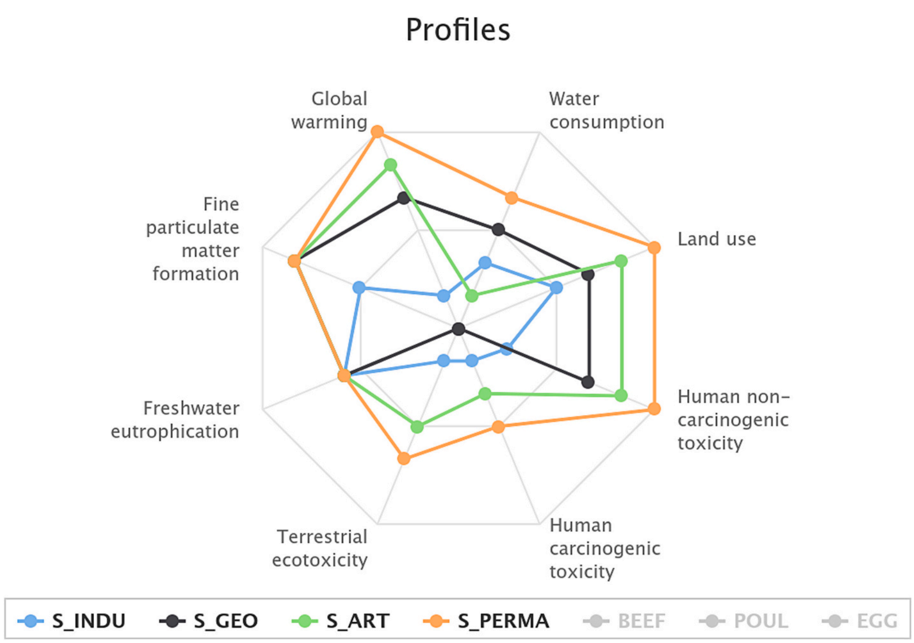

Fig. 4. Radar plot comparing the environmental performance of spirulina systems across all midpoint indicators (D-Sight, 2025).

figures, its electricity supply (in kWh) was 47 to 380 times greater than that of S_INDU, S_ART and S_PERMA.

Next, the analysis of the land use indicator was complemented with a qualitative approach because, as a reminder, the direct occupation of the land and the nature of the land was not represented accurately enough by the indicator. According to the available data, S_INDU, S_GEO and S_ART did not host any biodiversity on their production sites (concrete or sterile soil). In addition, S_GEO was located in a climate that was unfavourable to plant growth, unlike S_INDU and S_ART, which could have encouraged biodiversity but did not. On the other hand, S_PERMA was located on a permacultural farm, rich in biodiversity and local species. This ecosystem was even more beneficial in that it contrasted with the dominant monoculture of the surrounding vineyards, which left the soil devoid of plant cover after the grape season. So, from the point of view of land use management, S_PERMA appeared to be the most favourable. This qualitative analysis was in line with the quantitative

Table 4
S_INDU – impacts breakdown for each phase (midpoint indicators).

Impact category	Unit	Total	Cultivation	Harvesting	Processing	Distribution
Global warming	kg CO_2 eq	25.53	14.48	8.33	2.46	0.27
Fine particulate matter formation	kg $PM_{2.5}$ eq	0.04	0.02	0.01	0	0
Freshwater eutrophication	kg P eq	0.01	0.01	0	0	0
Terrestrial ecotoxicity	kg 1.4-DCB	165.52	141.2	9.89	13.42	1.01
Human carcinogenic toxicity	kg 1.4-DCB	3.64	2.69	0.59	0.34	0.01
Human non-carcinogenic toxicity	kg 1.4-DCB	25.06	18.68	3.8	2.53	0.06
Land use	m^2a crop eq	0.92	0.57	0	0.34	0
Water consumption	m^3	0.54	0.5	0.02	0.02	0

results of the land use indicator (0.92 m^2a crop area for S_INDU and 0.25 m^2a crop area for S_PERMA).

2.3.2. Analysis by production phase

Tables 4–7 present the results of the midpoint indicators for the four production phases of each spirulina system: the orange cells represent the phase that contributed most to the impact for each indicator. In S_INDU, S_GEO and S_ART, the cultivation phase generated the most significant impact for all indicators. The impact of this phase was largely due to certain fertilisers (mainly urea, sodium bicarbonate and sodium nitrate) and electricity consumption (for S_INDU and S_GEO only). The impact of the cultivation phase and fertilisers in terms of GWP had already been described in (Ye et al., 2018; Fernández-Ríos et al., 2024; Quintero et al., 2021). A comparison of the cultivation phase of S_INDU, S_GEO, S_ART, and S_PERMA (Fig. 5) showed a decreasing trend similar to that observed for the total impact of the systems (S_INDU had the highest impact and S_PERMA the lowest). S_PERMA, which applied a reasoned use of fertilisers and used two fertilisers derived from the valorization of either underused resources or resources that would otherwise have been environmentally harmful, had the most favourable cultivation phase in terms of environmental impact.

By comparing the impact of 1 kg of all the fertilisers used in the cultivation phase of the four spirulina production systems (Fig. 6), we could determine whether the impact of the three fertilisers identified as the most harmful was due to intrinsic harmfulness (fertiliser itself harmful, even in small doses) or to intensive use (fertiliser itself not very harmful, but used in large quantities). The impact of sodium bicarbonate was explained by the sum of average intrinsic harmfulness (average high impact per unit mass) and intensive use (fertiliser, whose amount was the highest in S_INDU, S_ART and S_PERMA). The impact of urea and sodium nitrate was not due to intensive use (used only in small quantities), but to high intrinsic harmfulness (high impact per unit mass).

Unlike the cultivation phase, the harvesting, processing and distribution phases had a marginal impact, with three exceptions. First, in S_INDU, the harvesting phase accounted for more than half (8.33 kg CO_2 eq) of the cultivation phase's impact on total global warming (respectively 8.33 kg CO_2 eq and 14.48 kg CO_2 eq for 1 kg of protein content), making it the only system with this profile. Secondly, the processing phase of S_INDU had a significant impact on land use, due to the use of microcrystalline cellulose, colloidal silicon dioxide and electricity from the conventional energy mix. Thirdly, S_PERMA was distinguished by a distribution phase that had a much greater impact than the other systems – especially on global warming (2.62 kg CO_2 eq) and terrestrial ecotoxicity (47.3 kg 1.4 DCB) – although the impact of the cultivation phase remained dominant. Road transport by refrigerated lorry (from the distribution phase) and sodium bicarbonate (from the cultivation phase) were the main impact factors. By comparing the impact of 1 tkm of the modes of transport used in the four spirulina production systems (Fig. 7), it emerged that for the same distance weighted by mass, the refrigerated lorry used in S_PERMA had an intrinsically high harmfulness (with an impact per tkm equal to more than three times that of transport by non-refrigerated lorry and approximately 50 times greater than that of sea ship). Although the distance covered during the distribution phase of S_PERMA was 10 times less than that covered in S_INDU, the intrinsic harmfulness of the refrigerated lorry was sufficient to make the distribution phase of S_PERMA 5 to 10 times more harmful than that of S_INDU (varying according to the endpoint indicator analysed) (Fig. 8).

2.4. Discussion

The findings suggested that spirulina production is a promising source of protein compared with conventional beef production. The environmental benefits of spirulina production, regardless of method, are significant compared with beef production. However, these benefits are more nuanced when compared with poultry and egg production, according to the ReCiPe 2016 methodology. When comparing the four spirulina production methods, our results suggested that local permacultural production is preferable, followed by local artisanal production. Geothermal production in Iceland ranked third, while industrial production in China ranked last. Indeed, the environmental benefits of spirulina as a protein alternative proposed as part of the protein transition are highly dependent on the production system. Our results indicated that only the permacultural system had better environmental potential than the modelled poultry production. These results indicate that the choice of production system, location, and distribution mode are key factors to achieving the goal of reducing environmental impacts of protein production and consumption, which is the aim of the protein transition.

Our results were in line with the existing literature. In terms of GWP, water consumption and land use, several studies showed that beef has a higher environmental impact than poultry and eggs, per kg of protein produced (De Vries and de Boer, 2010; Møller and Samonstuen, 2023). Regarding the environmental impact of spirulina production compared with beef, (Tzachor et al., 2022a; Tzachor et al., 2022b) confirmed that Icelandic geothermal spirulina production has a better profile for these three indicators. However, no study compared the environmental impacts of other spirulina production methods with those of beef. Similarly, the literature did not allow us to assess the environmental potential of spirulina production compared with conventional poultry and egg production. Regarding the comparison of impacts between previous LCAs on spirulina and our results, earlier studies reported highly variable outcomes for the global warming, water use, and land use indicators, depending on the production system (Ye et al., 2018; Tzachor et al., 2022a; Tzachor et al., 2022b; Fernández-Ríos et al., 2024; Papadaki et al., 2017; Quintero et al., 2021). Our study exhibited similar variability, but our results fell within the same range as those of the previous studies. Finally, (Fernández-Ríos et al., 2024) confirmed that, in terms of GWP, small-scale, local spirulina production has a better environmental profile than intensive production abroad, as analysed in (Ye et al., 2018).

Our study had some limitations that should be highlighted in order to

Table 5
S_GEO – impacts breakdown for each phase (midpoint indicators).

Impact category	Unit	Total	Cultivation	Harvesting	Processing	Distribution
Global warming	kg CO_2 eq	11.12	10.70	0.16	0.20	0.06
Fine particulate matter formation	kg $PM_{2.5}$-eq	0.01	0.01	0.00	0.00	0.00
Freshwater eutrophication	kg P-eq	0	0	0	0	0
Terrestrial ecotoxicity	kg 1.4-DCB	772.24	751.18	17.79	2.50	0.77
Human carcinogenic toxicity	kg 1.4-DCB	11.68	11.36	0.27	0.05	0.01
Human non-carcinogenic toxicity	kg 1.4-DCB	13.92	13.50	0.22	0.18	0.03
Land use	m^2a crop eq	0.68	0.66	0.01	0.01	0
Water consumption	m^3	0.47	0.46	0.01	0.00	0

Table 6
S_ART – impacts breakdown for each phase (midpoint indicators).

Impact category	Unit	Total	Cultivation	Harvesting	Processing	Distribution
Global warming	kg CO_2 eq	5.93	5.68	0.05	0.15	0.06
Fine particulate matter formation	kg PM2.5 eq	0.01	0.01	0	0	0
Freshwater eutrophication	kg P eq	0	0	0	0	0
Terrestrial ecotoxicity	kg 1.4-DCB	97.36	87.42	2.47	5.99	1.48
Human carcinogenic toxicity	kg 1.4-DCB	2.37	2.19	0.05	0.12	0.01
Human non-carcinogenic toxicity	kg 1.4-DCB	13.58	13.1	0.12	0.31	0.04
Land use	m^2a crop eq	0.55	0.44	0.01	0.1	0
Water consumption	m^3	0.71	0.71	0	0	0

Table 7
S_PERMA – impacts breakdown for each phase (midpoint indicators).

Impact category	Unit	Total	Cultivation	Harvesting	Processing	Distribution
Global warming	kg CO_2 eq	4.57	1.5	0.06	0.39	2.62
Fine particulate matter formation	kg PM2.5 eq	0	0	0	0	0
Freshwater eutrophication	kg P eq	0	0	0	0	0
Terrestrial ecotoxicity	kg 1.4-DCB	77.62	23.39	2.3	4.63	47.3
Human carcinogenic toxicity	kg 1.4-DCB	1.28	0.63	0.04	0.11	0.5
Human non-carcinogenic toxicity	kg 1.4-DCB	5.85	4.03	0.04	0.35	1.43
Land use	m^2a crop eq	0.25	0.14	0.01	0.03	0.07
Water consumption	m^3	0.43	0.32	0	0.11	0

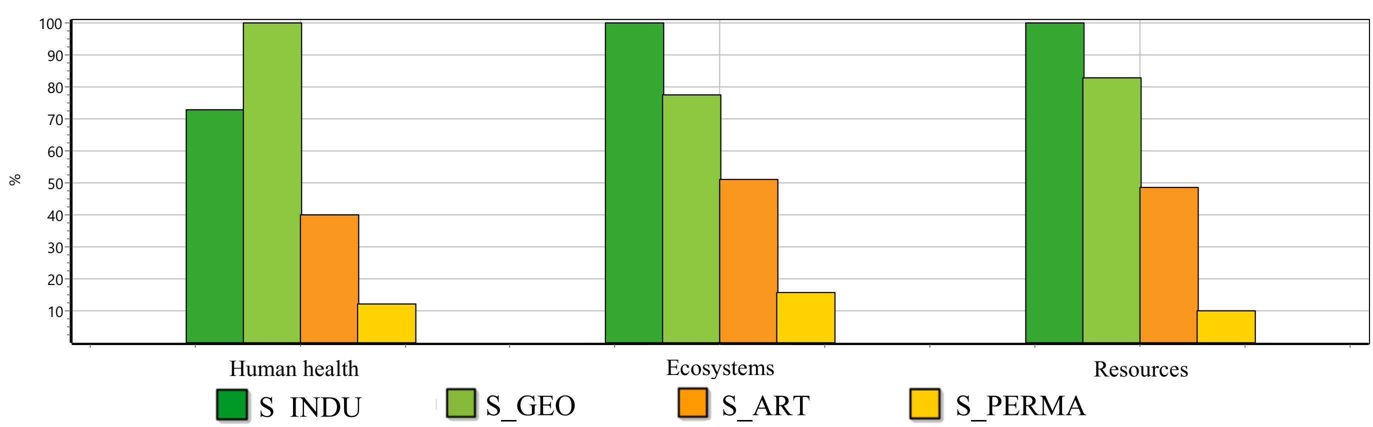

Fig. 5. Comparison of the cultivation phase of spirulina systems - endpoint indicators (PRé, 2024).

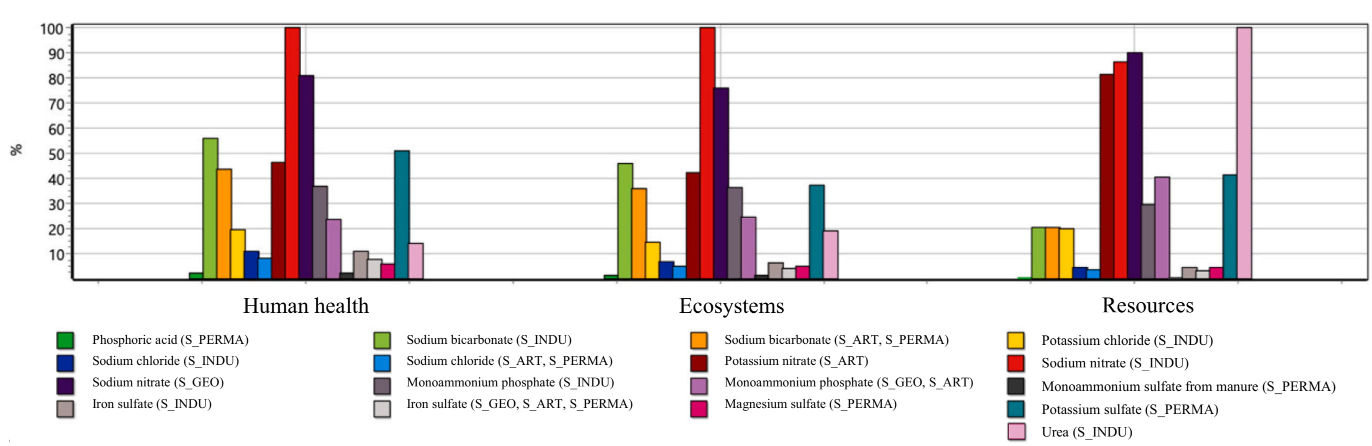

Fig. 6. Comparison of 1 kg of each fertilisers of spirulina systems - endpoint indicators (PRé, 2024).

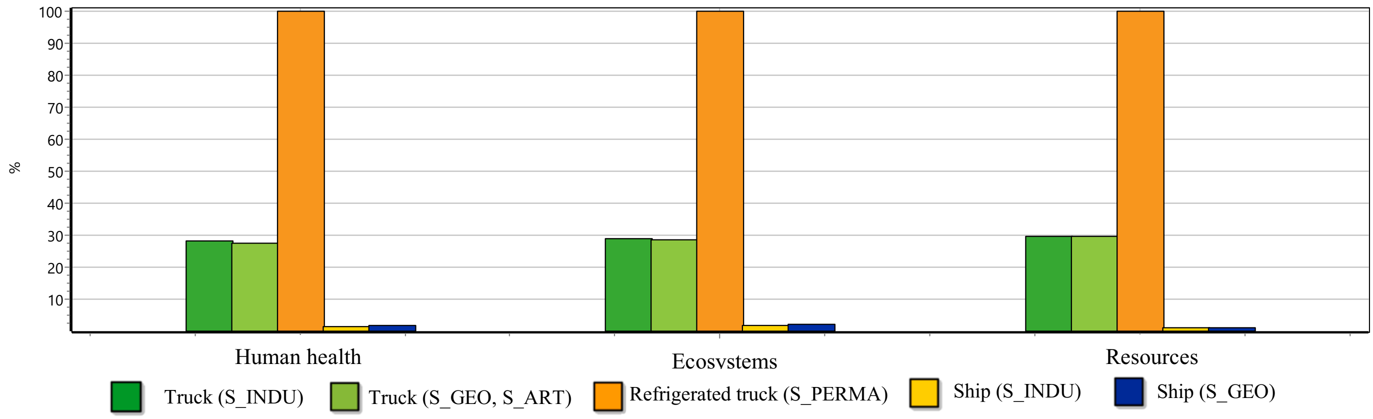

Fig. 7. Comparison of 1 tkm with each mode of transport of spirulina systems - endpoint indicators (PRé, 2024).

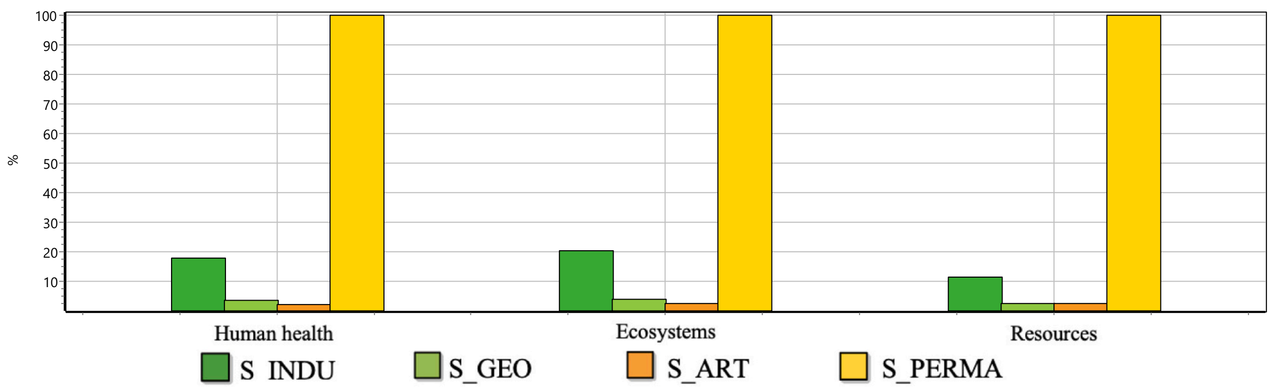

Fig. 8. Comparison of the distribution phase of spirulina systems – endpoint indicators (PRé, 2024).

contextualise our results. On the one hand, our LCA did not allow us to differentiate the environmental impact of the various methods of producing beef, poultry or eggs, as our reference systems referred to an average of many European scenarios. It is therefore important to add nuance to the interpretation of our conclusions. In the future, it would be relevant to assess the impact of the four spirulina production methods studied in our LCA by comparing them with several production methods for the same animal protein (e.g. local and organic poultry production vs. intensive and distant poultry production). On the other hand, this LCA had other methodological limitations, as mentioned in "2.1.7 Methodological limitations".

Our study provided a convincing answer to our research question, while raising new questions that opened up prospects for future research. The permaculture system (S_PERMA), identified as the most promising option in terms of sustainability, deserves to be explored in depth in order to define how its scaling-up might be possible in practice. It would be relevant to examine whether the environmental impact of the permacultural system could be reduced if spirulina were marketed in dry form, thus avoiding transport by refrigerated lorry (but requiring on the other hand a more harmful processing phase necessary for drying and packaging dry spirulina or spirulina tablets). In addition, it would be interesting to analyse the environmental benefits and limitations of setting up a network of small-scale permacultural spirulina producers in Europe, in order to develop local food circuits. The producer confirmed that permacultural production is technically viable in latitudes cooler than the south of France.

Another perspective that is inextricably tied to the large-scale development of spirulina production concerns the adoption of the practice of eating seaweed in Western countries. It would be interesting to analyse the structural barriers and levers for change in protein consumption practices by studying various aspects such as financial and social accessibility, cultural barriers to seaweed consumption, the legislative, regulatory and infrastructural framework, the relationship between production scale and environmental impacts, the governance of the seaweed sector and, more generally, of the protein sector. To understand the differences in the diffusion of seaweed consumption, it would be relevant to analyse the differences between South-East Asia, where seaweed is commonly consumed, and Europe, where it remains marginal.

The quality of the product marketed should also be included in the analysis. For example, production in China is probably more exposed to atmospheric pollution, especially in the absence of protection above the basins. It would be relevant to assess whether there are differences in quality between two certified spirulina, one produced in China and the other in Europe.

Finally, although increasing the proportion of plant and alternative proteins and decreasing the proportion of animal proteins is in line with the objectives of the EU Green Deal and Common Agricultural Policy, with increased support for legume crops and encouragement to develop other sources of protein, such as insects, algae or in vitro meat (European Commission, 2018; Bouillot, 2020; European Parliament, 2023), the success of non-animal protein products on European markets remains modest (Siegriest and Hartmann, 2023). These alternatives do not appear to replace animal proteins and thus reduce meat consumption. On the contrary, what is observed is an increase in the total quantity of proteins consumed, with the consumption of plant proteins adding to that of animal proteins (Siegriest and Hartmann, 2023; Mancini and Antonioli, 2022). As presented in (Mancini and Antonioli, 2022), even though the European market for vegetarian and vegan meat alternatives has grown significantly (+68 % between 2018 and 2020), the consumption of these alternatives remains low (e.g., €3.3 per capita in 2020). Furthermore, (Siegriest and Hartmann, 2023) suggested that plant-based alternatives are not always consumed instead of meat, and in some cases, meat consumption continues to rise alongside, increasing the total amount of protein consumed per capita. Although several studies assumed a direct substitution effect, with alternative proteins replacing meat, evidence supporting the existence of this substitution effect is lacking because of limited studies (Mancini and Antonioli, 2022). Thus, increased availability of alternative proteins does not automatically lead to reduced meat intake, but may instead lead to a multiplication of impacts, with the environmental impacts of increased total protein consumption accumulating (Mancini and Antonioli, 2022). This observation reflects the phenomenon of stacking (i.e., adding new alternatives to old ones without displacing or phasing out the older ones they were intended to replace, potentially leading to a multiplication of impacts). This has also been observed in energy and mobility transitions, where new, more sustainable energy sources or modes of transport accumulate alongside existing ones, ultimately increasing the total environmental impact (David, 2017; Yadav et al., 2021). The possibility of a stacking phenomenon in the protein transition supports the need to adopt measures to accompany the insertion of alternative sources of protein on the markets (e.g. reflecting the environmental cost of animal proteins in the purchase price, reducing subsidies allocated to livestock farming, changing social norms relating to the consumption of animal proteins) (Siegriest and Hartmann, 2023). Another possibility would be to open up the discourse of exnovation (i.e. the deliberate pushing of undesirable technologies out of the system), as has already been discussed for the energy transition, which also presents a case of technological stacking (David, 2017; Yadav et al., 2021). These aspects could be the subject of a future study.

3. Conclusion

This study highlighted the environmental potential of spirulina as a protein alternative in the food transition. Through the comparative cradle-to-consumer assessment of the environmental impacts of four spirulina production systems and its perspective with three reference systems (beef, poultry meat, eggs), our findings indicated that spirulina production is a promising source of protein compared to conventional beef production. The environmental benefits of spirulina production, regardless of the production method, were significant compared to beef production, with spirulina emitting up to 98 % less CO_2 than beef (4.56 vs. 187.17 kg CO_2 eq), however, these benefits were more nuanced when compared to poultry and egg production, according to the ReCiPe 2016 methodology. Our findings showed that only the permacultural system had a better environmental potential than the modelled poultry production. When comparing the four systems of spirulina production, our findings suggested that local permacultural production had the most promising environmental profile, followed by local artisanal production, then geothermal production, and finally the industrial production. Permacultural spirulina used 73 % less land and showed a 77 % drop in human toxicity compared to the industrial system. Thus, the environmental benefits of spirulina as a protein alternative in the protein transition were highly dependent on the production system. For all four systems, the cultivation phase was the one generating the most impacts, although in the permacultural system, the distribution phase also contributed significantly. The harvesting and processing phases played a marginal role in all systems. The high share of responsibility of certain inputs in the total impact of the cultivation phase was explained by an overlap of (i) the high harmfulness of the input per unit mass and (ii) the total quantity used by the producer. The proportion of these two factors varied from one input to another. Moreover, practicing a reasoned use of fertilisers allowed to reduce the impact of the cultivation phase. Thus, the choice of the method of production, the location of production and the mode of distribution are key factors to be considered in order to fulfill the goal of reducing the environmental impacts of protein production and consumption, targeted by the protein transition.

This study had three main limitations. First, infrastructure and direct land use were excluded from the analysis due to data gaps. Indirect land use was included and supplemented with a qualitative assessment. Second, as water use practices varied across systems, comparability was ensured through a 10-year amortisation method, accounting for whether systems renewed water annually or retained it over time. Third, the reference animal protein systems did not capture the full diversity of available production methods, relying instead on generalized European models based on Agri-footprint data.

Our study focused solely on the environmental impacts of producing an alternative source of protein. We have opened up research avenues for further study, such as the study of the conditions necessary for the large-scale development of permacultural spirulina, the assessment of the impacts of other protein sources in a more differentiated way, the analysis of the structural barriers to the adoption of spirulina in Western diets, as well as the stacking problems and the need for exnovation in the food sector. Finally, beyond environmental considerations, it is essential to integrate socio-economic and institutional dimensions to ensure an efficient, fair, and sustainable food transition.

CRediT authorship contribution statement

Valentina Vannini: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Wouter M.J. Achten:** Writing – review & editing, Validation, Supervision.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2025.180184.

Data availability

Data will be made available on request.

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