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Conceptual design and environmental evaluation of the Biorefinery approach for R-phycoerythrin extraction and purification

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ABSTRACT

Marine algae are considered promising resources both at present and in the near future. Their availability, together with their molecular structure and properties, increases their applicability in various sectors: food and feed, cosmetics, pharmaceuticals and bioenergy. However, the "bio" qualification does not always imply a lower impact compared to fossil-based process schemes. Therefore, to verify the suitability of algae-based scenarios from a sustainable and circular perspective, it is necessary to assess their sustainability potential through process modelling (scaling up from laboratory scale to evaluate their potential at commercial level), environmental assessment (using the Life Cycle Assessment (LCA) method) and circularity analysis (by quantifying circularity indicators focusing on recovery, waste management and effective use of resources). In this context, this research report focused on the techno-economic assessment (TEA) and LCA of three alternative scenarios based on the extraction of R-phycoerythrin from offshore harvested macroalgae: water extraction followed by enzymatic digestion (S01), ultrasound-assisted extraction (S02) and water extraction (S03). In addition, the evaluation of environmental, social and circularity indicators and the application of the Greenness Grid methodology were included. According to the results obtained, S01 is the most promising alternative among the three scenarios due to its process productivity, lower environmental impact and potential sustainable scenario score according to the Green Chemistry assessment. Regarding the economic perspective, S03 is the only one that does not reach economic viability. Future studies should focus on improving process efficiency, promoting the use of renewable energy resources and supporting technological progress in emerging extraction processes.

1. Introduction

The blue economy aims to promote the sustainable use of marine resources [1–3]. In this context, the exploitation of marine algae offers noteworthy opportunities, mainly for two reasons: (1) their possible potential to reduce environmental impacts such as climate change and eutrophication, given their ability to sequester carbon and nutrients [4–6] and (2) their content of bioactive compounds and reduced lignin content, making them an interesting resource for the production of high value-added compounds [7–9]. In fact, according to market trends, the seaweed market is expected to reach a value of $24.92 billion by 2028, with a CAGR of 7.51 %, with Europe being one of the leading regions in seaweed valorization [10].

On the other hand, one of the main concerns regarding the sustainability of the marine environment is eutrophication, caused by excess nutrients, mainly due to industrial development and uncontrolled emissions [11–13]. In this approach, off-shore macroalgae cultivation can be considered as a solution to reduce the presence of nutrients in the aquatic environment, since during algae growth, they absorb both nitrogen and phosphorus, in quantities that depend on the species itself, but sufficient to counteract the nutrient emission from commercial activities and promote an environmental benefit [1,14,15].

It has been shown that harvesting seaweed from the sea could have environmental benefits, although this depends on the way it is harvested and transported. It is at these stages that the degree of sustainability in the use of seaweed as a raw material needs to be assessed, taking into account all stages of the life cycle, from production to final disposal [16,17]. There is no point in increasing environmental benefits during

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exploitation if they are the same or worse than those of non-renewable fossil resources analogues. It is important to keep in mind that the term "bio" is not always synonymous with sustainability, so the use of methodologies for its evaluation in the algae sector is fundamental.

It is within this approach that this research article has been developed, which includes a modeling, techno-economic and sustainability analysis of an offshore macroalgae valorization process for the extraction of phycoerythrin, a pigment widely used in several industrial sectors. Phycoerythrin is a natural-based fluorescent protein extracted from red algae with interesting optical and physicochemical properties that makes it a versatile and widely used resource in various market sectors [18,19]. It could be used as a fluorescent marker in biotechnological processes for the analysis or separation of cell populations [20]; as a conjugate in antibody-drugs in the pharmaceutical sector [21,22]; as a natural colorant in food, offering a more sustainable and ecological colorant to avoid the use of synthetic dyes [23,24]; used also in the cosmetic sector due to its characteristic red-color, helping to produce more eco-friendly cosmetic formulations [25,26]. The importance of phycoerythrin in all these sectors is also evident when analyzing its market trends as, according to the more recent statistics [27], its market is expected to grow at a compound annual growth rate of 8.1 %, reaching a market value of $10.3 million by 2034.

In this techno-economic and sustainability analysis, the stages of seaweed harvesting at sea, transport to the plant and valorization have been included. In addition, three alternative extraction scenarios were evaluated, taking into account conventional and emerging technologies. It should be noted that different seaweed species were considered in the modeling of these scenarios, as no literature was available to compare the same seaweed with different extraction methods. For the environmental assessment, Life Cycle Assessment [28,29] was applied in combination of sustainability and circularity indicators available in literature and certification schemes. Finally, the principles of Green Chemistry were also assessed using the Greenness Grid methodology [30,31]. To this end, it is hoped that the results obtained in this research article will be useful for researchers, policy makers and stakeholders to make decisions and focus actions on the development of large-scale macroalgae bioprocesses.

2. Methodology

2.1. Off-shore harvesting of the algae and transportation to the facilities

The inventory for this first stage has been built based on primary data provided by Vetik®, a company that harvests macroalgae in natural environments as a raw material for value-added products. For this purpose, a survey of the main material and energy flows necessary on a yearly basis was designed. The resulting life cycle inventory can be found in Table 1-Supplementary Material.

Seaweed is harvested by a trawler departing from the port of Taaliku (Saare, Estonia), after a 40-minute route in an area where seaweed grows naturally in the open sea. Such an area is about 7 m deep, where wild algae are caught wild grown with a characteristic trawl net: a rectangular metal frame covered with a net that is dragged behind the boat at very low speed and unloaded 10–15 times until the boat is full. Therefore, inputs related to the construction (boat infrastructure), use (marine diesel and trawl nets) and maintenance (antifouling, lubricating oil and boat paint) of the trawler were considered.

The annual catch is 500 tons, of which the majority (92.9 %) is algae, 5 % is clams, and the rest is discarded material such as sand. The daily catch is about 10 tons. This means that the vessel catches seaweed 50 days a year. Based on this harvesting time, the material flows for the maintenance of the trawler were allocated to the algae harvesting according to this operational ratio (approximately 14 %), as the remaining days could be allocated to other tasks such as fishing. For the vessel infrastructure, a useful life of 40 years has been assumed, taking into account the steel needed to build the hull, as it represents up to 80 % of the total weight. For this purpose, Eq. 1 was used to estimate the weight of a vessel hull from its dimensions and material properties.

$$\text{Hull weight (ton)} = L \cdot B^2 \cdot T \cdot \text{Specific gravity}_{\text{steel}} \quad (1)$$

Where L is the length of the vessel (11.9 m), B the beam of the vessel (3.6 m), T the average hull thickness, which usually varies from 6 to 12 mm (0.01 m) for medium-sized vessels and specific $\text{gravity}_{\text{steel}} = 7.85$ (dimensionless). Regarding the single trawl net, it weights 30 kg and its main material is nylon with a service life of 5 years [32].

Likewise, there are certain flows that are consumed during ship operations and generate emissions. However, due to the lack of monitoring, these had to be estimated and modelled using secondary data. Consequently, the environmental impacts associated with the combustion of marine diesel, the emissions associated with the consumption of lubricating oil were considered.

Depending on the type of marine diesel burned, emission factors for the different gases produced were taken from two references: (i) carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) from the IPCC (Intergovernmental Panel on Climate Change) guidelines, and (ii) sulphur and oxides, particulate matter (PM), heavy metals, among others, have been compiled from the Air Pollution Emissions Inventory Guidebook [33]. For lubricating oil consumption, CO_2 emissions were estimated using Eq. 2, assuming a calorific value of 0.0418 TJ per kg [33].

$$CO_2 \text{ emissions (ton)} = LC \cdot CC_{\text{lube oil}} \cdot ODU_{\text{lube oil}} \cdot \frac{44}{12} \quad (2)$$

Where LC is the lubricant consumption (1 ton: 41.8 TJ), $CC_{\text{lube oil}}$ the carbon content of lube oil (20 kg $C \cdot TJ^{-1}$), $ODU_{\text{lube oil}}$ the default value based on the fraction oil/grease (0.2) and 44/12 = molecular mass ratio of CO_2/C.

Regarding the production and consumption of antifouling, it has been possible to estimate using information on its average chemical composition, assuming that two thirds of the protective layer covering the vessel will be discharged at sea [34]. When the vessel arrives in port, the catch is unloaded by means of a crane, which requires the use of electricity. An average consumption of 5.5 kW per hour is assumed, with 1.5 hours being the time required for unloading. Finally, each catch (i.e., 10 tons) is transported by truck, which travels a distance of 53.2 km to reach the facility.

2.2. Pigment recovery alternatives. Description of scenarios

As for the extraction alternatives, those are evaluated based on bibliographic data, which have been considered for the techno-economic evaluation of the process through the SuperPro Designer tool. The production capacity of the facility has been adapted to the collection capacity (500 ton/year). On the other hand, it should be noted that all the extraction alternatives require a pretreatment stage, based on a washing stage, in which the sediments found in the algae are removed, followed by a freeze-drying stage, to remove the water prior to the extraction stage.

2.2.1. Scenario 01. Water extraction and enzymatic digestion

The first scenario to be evaluated is based on a water extraction procedure to obtain both phycobiliproteins (phycoerythrin) and chlorophyll a, but the latter in small amounts. The modelling of the process has been based on the research report developed by Lee et al. (2017), using as algae the species *Palmaria palmata*, a red macroalgae that grows mainly in the Atlantic and Pacific Ocean [35,36].

The process was divided into three main stages: (1) Pretreatment, based on algae washing and freeze-drying (freeze drying stage is used for the lyophilization of the macroalgae, as it increases the extraction yield of the phycoerythrin, considering an output stream with 5 % of water content). Concretely, from the 500 tons of the macroalgae, with a mass water content of 56.40 %, a total of 229.47 tons are obtained after the freeze-drying to be further treated in the following process Section (2) Extraction of phycoerythrin and chlorophyll-a: the extraction yield amounts to 1.60 kg phycoerythrin per ton of algae for Scenario 01, 0.46 kg/ton in case of Scenario 02 and 0.02 kg/ton for Scenario 03, thus obtaining 797.7 kg, 230.3 kg and 7.81 kg from the 500 tons of initial wet weight macroalgae for Scenario 01, Scenario 02 and Scenario 03, respectively. And (3) recovery and purification of the extracted compounds. After freeze-drying, the algae are reduced in size to increase the contact area with the extracting agent, in this case water, and thus increase the yield of the first extraction stage. In addition to water, ammonium sulphate must be added to promote greater efficiency in the process. This is preceded by a centrifugation stage to recover the solvent, followed by a diafiltration stage to remove those compounds with a molecular weight higher than that of phycobiliproteins and chlorophyll, and to improve the yield of the enzymatic digestion. This stage, which takes places just after the water extraction one, is carried out considering a proteases-enzymes concentration of 10 mg/L at 70 °C with a weight ratio of 1:100 enzyme: biomass for a process time of 3 hours. After this enzymatic process, an ethanol treatment stage is carried out, with an ethanol concentration of 10 mg/mL at 100 °C for 1 h. Finally, the reactor output stream is centrifuged to remove the solvent and dried with a spray dryer.

From these data, large-scale modelling was considered for a production capacity of 500 ton/year of harvested algae, which are processed in batches of 3.1 tons of algae. The process inventory for the life cycle analysis is included in Table 2-Supplementary Material, with all the inputs and outputs of the system.

2.2.2. Scenario 02. Ultrasound assisted extraction

The second proposed scenario is based on an ultrasound extraction batch procedure and has been modelled according to the results obtained with *Sarcopeltis skottsbergii*, which is a red algae endemic to southern Chile, which is mainly marketed as a source of carrageenan, but which also has a significant R-phycoerythrin content [37,38]. The process stages of Scenario 2 are similar to those of Scenario 01, but they differ in the extraction procedure and the purification stages (Fig. 2). The operating conditions for ultrasound-assisted extraction consider water as the extraction agent, an amplitude of 60 % and a process time of 20 min. Immediately after extraction, the output stream is centrifuged to remove water, which is recirculated to the process, and the high molecular weight compounds found in the algae, also an ultrafiltration step is also required to remove and recover phycoerythrin and chlorophyll-a.

In terms of the production capacity of the plant, in this case the batch time is shorter than in the previous scenario, requiring a total of 27 h per batch, and thus a greater number of batches per year are required to manage the total mass of algae collected annually. Considering both aspects, the amount of input material amounts to 2.6 tons of algae per batch. Table 3-Supplementary Material shows the main inputs and outputs related to the process.

2.2.3. Scenario 03. Enzymatic extraction

The third scenario is based on an enzymatic extraction procedure for the species *Palmaria palmata* species. All the data used for the large-scale modelling have been published elsewhere [39]. In this case the extraction is based on an enzymatic procedure, using water as the main solvent, sodium acetate as pH buffer to maintain pH in a range of 5–8.5 and thermolysin (a metalloendopeptidase enzyme). In terms of process conditions, the amount of enzyme required to be added amounts to 16.5 g/kg dry weight of algae, 40for an enzyme extraction time of 195 min [39]. With respect to the process conditions, the amount of enzyme that is required to be added amounts to 16.5 g/kg of dry weight of algae and a constant temperature of 40 °C. On the other hand, just after the enzymatic extraction, the hydrolysate is centrifuged in order to separate the solubilized compounds and macromolecules, and then the supernatants are ultrafiltrated in order to separate phycoerythrin and chlorophyll. Table 4-Supplementary Material shows the life cycle inventory associated with this third alternative.

2.3. Techno-economic and environmental assessment

In order to determine the economic feasibility of the extraction alternatives, a techno-economic assessment (TEA) has been developed as a process design and modelling tool to identify material and energy flows, equipment sizing and associated costs. In this particular work, the TEA was based, firstly, on the definition of the required equipment and its main characteristics (i.e., size, power, volume, etc.), secondly, on a cost-benefit analysis, in which the costs and the minimum selling price of the product are evaluated, and thirdly, on a simplified market analysis, seeking to identify the price of the chemicals, the purchase costs of the equipment, as well as the market value of the main products obtained, in this case, phycoerythrin and chlorophyll a.

In addition, to evaluate the environmental profiles of the proposed scenarios, the Life Cycle Analysis methodology, based on the ISO 14040 and ISO 14044 guidelines, was used. It consists of four main stages, starting with the definition of the functional unit and system boundaries, followed by the construction of the life cycle inventories, the development of the environmental assessment and ending with the interpretation of the results.

For the evaluated scenarios, a cradle-to-gate approach was considered, covering all stages from the extraction of raw materials to the factory gate, in this case, to the production of phycoerythrin and co-products, as shown in Fig. 1. EcoInvent was used as the database for the assessment (all the datasets used for the analysis are available in the Supplementary Material), while SimaPro was used as the software. Infrastructure maintenance is left out of the scope of the evaluation, since the focus of the assessment is the analysis of the environmental loads associated with the production process, in order to evaluate whether the proposed technology and biorefinery approach is sustainable or not. On the other hand, regarding the functional unit (FU), for the harvesting and collection stages, the annual catch has been selected as the FU, while for the extraction technologies, 1 batch of operation has been considered.

Regarding the assessment methodology, ReCiPe 2016 MidPoint (H) V1.07 and ReCiPe 2016 EndPoint (H/H) V1.07 were selected because the MidPoint provides a total of 16 impact categories related to potential environmental impacts, while the EndPoint includes all MidPoint scores in three damage categories, which is useful for comparing scenarios and selecting the most promising one. On the other hand, as for the MidPoint assessment, 11 out of the 16 impact categories were selected for evaluation in this research report, as they are the most relevant to the case studies under analysis.

In addition, once the hotspots of the environmental profiles were identified, sensitivity evaluations were developed to analyze the degree of improvement that could be achieved by modifying the process variables.

3. Results

3.1. Macroalgae off-shore harvesting and collection. Environmental assessment

The overall results for each impact category are shown in Fig. 2 for Stage 1 (harvest) for a functional unit of 464.5 tons of seaweed (Table 1-Supplementary Material). In addition, LCA studies in fisheries and aquaculture were also included for benchmarking (Fig. 1-Supplementary Material). These studies have been extracted from the NEPTUNUS project, which aims to support the transition to sustainability in the seafood sector through eco-labelling strategies.

Firstly, seaweed harvesting achieves the lowest values for all impact categories, being particularly remarkable in the case of FE and ME, as it

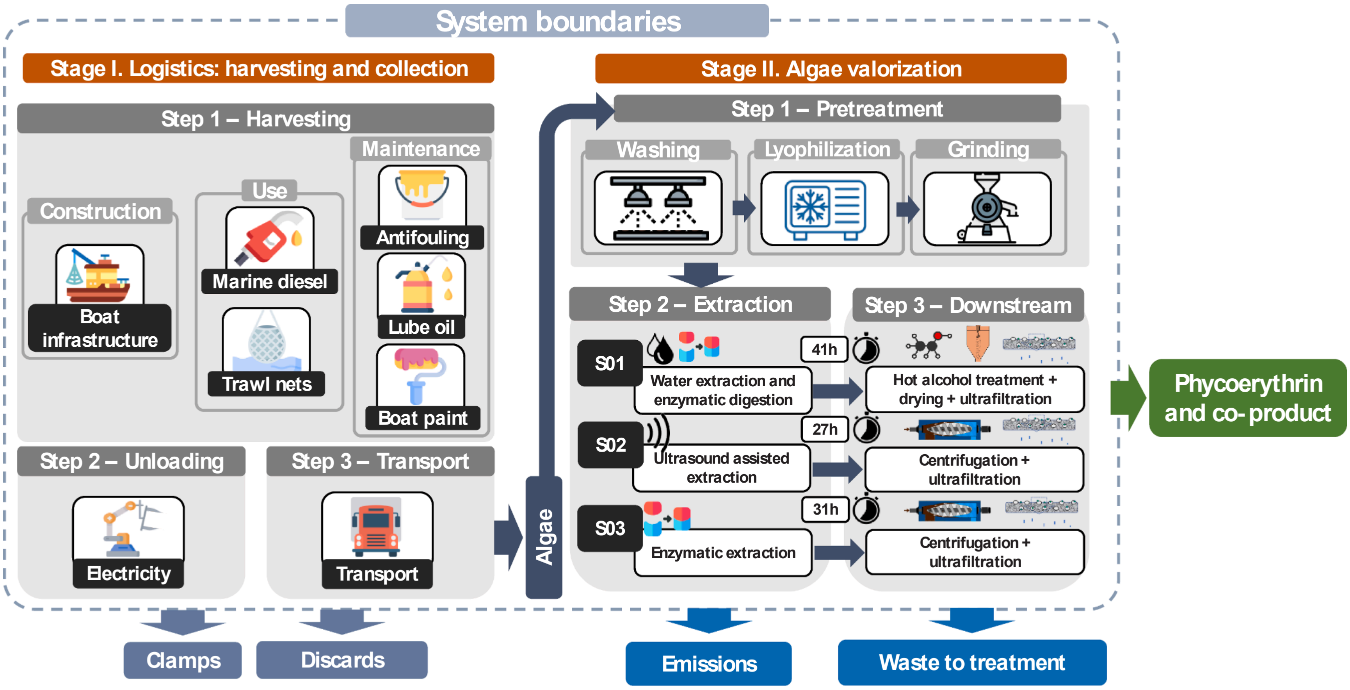


Fig. 1. Environmental profile of the Scenario 01: water extraction and enzymatic digestion to obtain phycoerythrin and chlorophyll a.

can fix N and P during its growth. In contrast, the octopus catch records the highest environmental impact in up to 5 different categories: GW, TA, FE, TET and FRS, followed by hake with 4 (SOD, FET, MET and HCNT). After these, tuna and mackerel fisheries occupy an intermediate position and finally, shellfish fisheries have the lowest environmental impact, except for HCT and ME. This may be partly due to the similarities between their harvesting processes. Scallop fishing is carried out by bottom trawling with a steel dredge and a polyethylene net while mussel farming is based on extensive marine aquaculture practices, requiring the use of auxiliary vessels and rafts.

It is also important to note that this comparison has been made from the perspective that all the case studies are somewhat related in the sense that they use vessels that require similar inputs for their use and maintenance. However, there are many differences, such as the fishing gear used, the distance to the catch area (fishing grounds) or the catch yield. Furthermore, although they have the same mass flow, they do not actually serve the same function, since shellfish are intended for food, while seaweed is intended to be used as raw material for the manufacture of value-added products. In addition to the above, it is also important to note that seafood products also do not serve the same function among themselves, as they vary in their nutritional profiles and edible portions when used as food. Therefore, despite all these factors, it is worth noting as a positive point that the comparison has provided a first approximation of the potential that naturally harvested seaweed could have, not only for industrial purposes but also as a raw material for food.

The full environmental profile of the first stage was evaluated by comparing stages 1 (harvesting), 2 (unloading) and 3 (transport) according to their relative weight for each impact category (Fig. 2**A**). As expected, harvesting is the step with the highest environmental impact, as up to 6 inputs have been considered, while unloading and transport have only one input each (i.e., environmental impacts related to electricity and transport, respectively). Moreover, the contribution of harvesting is higher for the HCT and TA categories, where it exceeds 94 %, while N and P fixation during algal growth practically offsets all the impacts caused by the other steps. Next, unloading is the step with the lowest environmental impact for all impact categories, with electricity consumption for the crane contributing to the HCNT impact category but with a minor value of 5.1 %. Finally, the transport of catches to the facilities is more prominent, being even the main contributor for 3 impact categories: TET (85.6 %), HCNT (55.5 %) and MET (51.5 %).

In order to provide a more complete study of the origin of the environmental impacts, the relative contributions have been disaggregated by input, as shown in Fig. 2**B**. Thus, as usual in fisheries LCA case studies of fisheries, the production and consumption (and corresponding emissions) of marine fuel is the main contributor with an average of 40.9 % for all impact categories, more pronounced in the cases of GW, SOD, TA and FRS. Transportation ranks second, with a relative average impact of 28.3 %, while vessel infrastructure ranks third, being the main contributor for HCT and FET. The latter differs from the literature as infrastructure, in this case the vessel, is usually not a major focus of impact due to its long life. However, in this case it can be attributed to the comparatively low impacts of the other inputs (e.g. antifouling, lubricating oil or vessel paint, all of which have less than 5 % relative impact) due to the limited use for seaweed harvesting, as there is a fixed maximum amount that can be extracted from the sea according to national regulations.

3.2. Extraction technologies. Techno-economic and environmental assessments

3.2.1. Scenario 01. Water extraction and enzymatic digestion

Process modelling with SuperPro Designer has allowed to identify the number of equipment as well as its main characteristics (i.e. size, flow capacity, diameter, volume, power, etc.). In the case of S01, the process flow consisted of 14 equipment which purchase cost, updated to 2023, amounts to $858,489, as shown in Table 1. The equipment that implies the higher costs is the freeze dryer, which requires two units, needed for the drying of the algae in the pretreatment stage, followed by the rotatory vacuum filtration equipment, which is part of the downstream stage. Other economic aspects that are directly related to each scenario are those of materials and utilities costs. In this case, the materials required in the process are ammonium sulfate, considering a purchase cost of 0.08 $/kg, ethyl alcohol, amounting to 0.75 $/kg, the enzyme *thermolysin*, which is the most expensive material required, 3.2 $/kg [40], and also water, which price has been stablished as 0.03 $/kg.

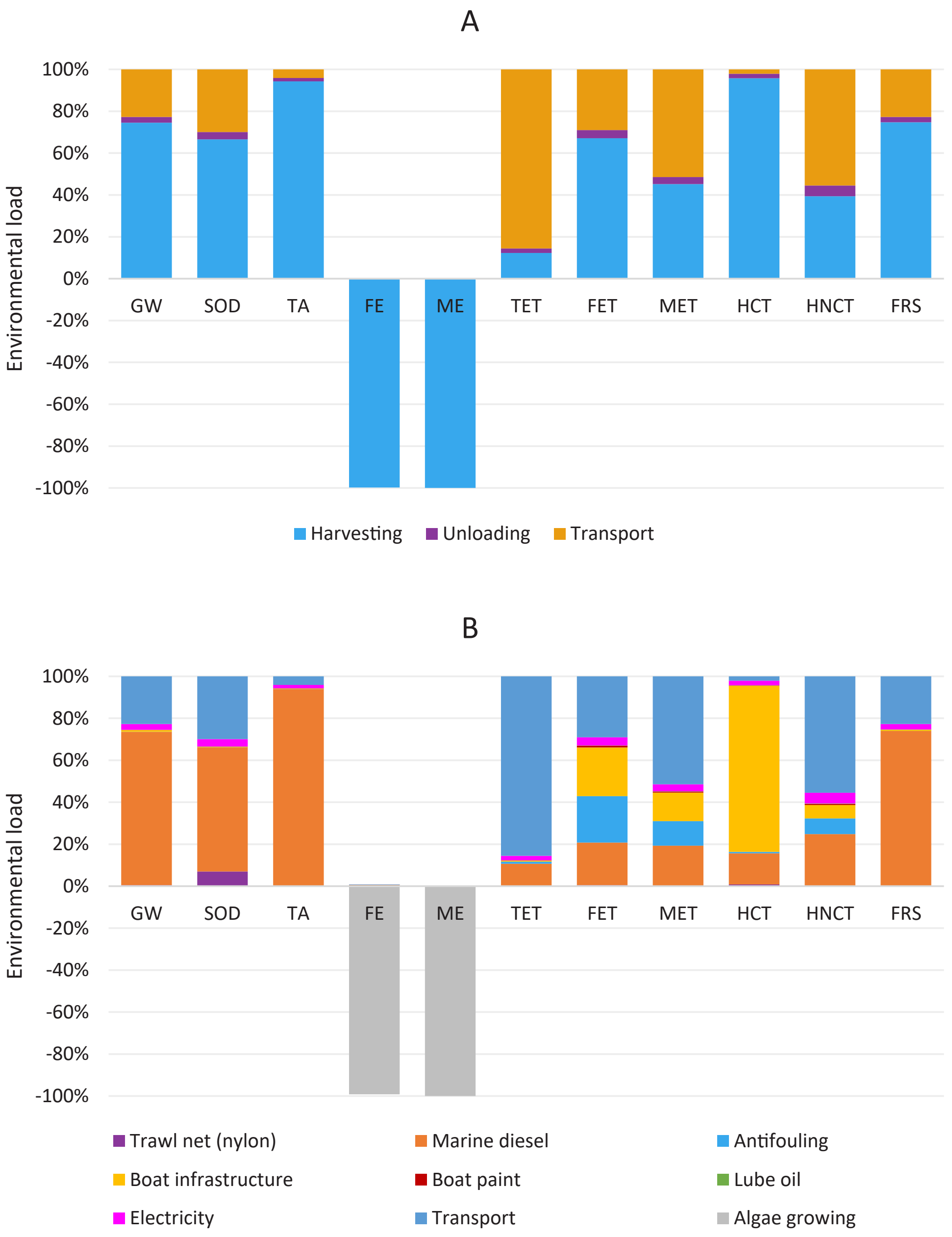


Fig. 2. (A) Environmental profile of the first stage divided by step and (B) Environmental profile of the first stage divided by inputs. Acronyms: GW (Global Warming), SOD (Stratospheric Ozone Depletion), TA (Terrestrial Acidification), FE (Freshwater Eutrophication), ME (Marine Eutrophication), TET (Terrestrial Ecotoxicity), FET (Freshwater Ecotoxicity), MET (Marine Ecotoxicity), HCT (Human Carcinogenic Toxicity), HNCT (Human Non-Carcinogenic Toxicity) and FRS (Fossil Resource Scarcity).

In terms of utilities, three mains are used in this scenario, steam, with a price of 12$/MT, electricity, 0.1 $/kWh, and cooling water, amounting to 0.05 $/MT. While the material costs were selected from literature and product providers, the ones of the utilities were taken from the SuperPro Designer database. On the other hand, the costs related with labor, have been estimated according to a correlation that considers the required operating labors according to the typology of processing steps (i.e. differentiation between processing steps that considers handling of particles and the ones that do not). As for the salary, it was set as 25 $/h, in accordance with the considerations of the EU-28. It should be noted that all costs associated with collecting and transporting the algae to the production facility were included in the "Materials" and "Labor" items.

Taking into account the above considerations, the financial metrics of net present value (NPV), payback and minimum selling price (MSP) were calculated, in order to evaluate whether the scenario is profitable or not. Considering 330 days of operation, as 30 days are used for maintenance, and a project lifetime of 25 years, the scores obtained show that the S01 is economically viable, since the NPV is positive, the payback time is lower than the expected lifetime of the production process and the MSP is significantly lower to the average market value considered (it should be mentioned that the price of phytoerythrin, according Sigma Aldrich®, amounts to 216,000 $/g, but it was reduced to a 0.05 % (108 $/g), as it was considered to be more realistic and also because it is expected that the product obtained will be sold to another company rather to an end user).

The environmental profile of the Scenario 01 shows that the energy requirements are the main hotspots of the whole process, with electricity being the one with the highest impact in the categories related with the toxicity (FET, MET, HCT and HCNT), except for the TET category, in which it is the steam the main contributor (Fig. 3A). This input is also the

Table 1
Techno-economic assessment results for Scenario 01. (1) The total equipment costs are updated to 2023 according to CEPCI INDEX.

Equipment	Capacity	Units	Purchase cost	Equipment	Capacity	Units	Purchase cost
Freeze Dryer	28.15 m^2	2	$90,155	Ultrafilter	1.15 m^2	1	$20,426
Grinder	42.21 kg/h	1	$14,121	Centrifuge	20.85 kW	1	$24,399
Tank	28.07 m^3	1	$19,449	Centrifuge	18.7 kW	1	$22,981
Spray dryer	169.73 L	1	$4352	Centrifuge	7.03 kW	1	$13,418
Bioreactor	28.09 m^3	1	$51,569	Rotatory vc filter	6.76 m^2	1	$69,005
Diafilter	20.62 m^2	1	$15,259	Hydrocyclone	0.7 m	1	$3210
Washer	252.5 kg/h	1	$26,333	**Total equipment cost ($) (1)**			**$858,489**

Item	Factor	Value
Direct costs		
Equipment delivered cost	1	$858,489
Equipment erection	0.2	$171,698
Piping	0.1	$85,849
Instrumentation and controls	0.1	$85,849
Electrical	0.1	$85,849
Buildings	0.1	$85,849
Site preparation	0.1	$85,849
Total capital cost of installed equipment	**1.7**	**$1459,432**
Indirect costs		
Design, engineering and construction	0.4	$343,396
Contingency	0.2	$171,698
Total fixed capital costs	**2.3**	**$1974,525**
Working capital (15 % total capital cost)		$296,179
Total Capital Cost		**$2270,704**
Other costs		
Labor cost	-	$1353,909
Utilities cost	-	$31,912
Materials cost	-	$66,317
TEA SCORES		
Net present value	> 0	Profitable
Minimum selling Price	5.64 $/g	Lower than market average
Payback	4 years	Lower than Project lifetime

one with the higher contribution to the GW, SOD, TA and FRS impact categories. The reason for the high impact of these requirements is mainly based on its non-renewable nature, which causes significant emissions on the above categories. On the other hand, the use of algae as a renewable source for the extraction of phycoerythrin has an environmental benefit in the FE and ME impact categories, due to its ability to fix 21 g N/kg dry matter and 4.5 g P/kg dry matter of algae during its growth [41].

On the other hand, regarding the solvent, since a significant amount of it could be recovered within the process, its contribution over the profile is not as important, having its maximum influence over the FRS impact category, reaching almost a 40 % of the total impact. The reason of this environmental load is mainly given of its production process, including the extraction of the materials, the energy needs, and the transportation activities. Besides, also regarding chemicals, a certain percentage of contribution is observed in the impact categories of TA, FET and TET. And, with respect to the enzyme, it has not been detected an important environmental load, reaching its maximum on the SOD impact category, which amounts to a 20 % of contribution.

Once the environmental profile was obtained, to improve it, a sensitivity assessment was performed. As the main hotspots are the energy and steam requirements, the evaluation was based on (1) reduction by a 20 % on the requirements of both electricity and steam, (2) use of renewable energy for the production of electricity, (3) use of steam coming from the energetic valorization of wood logs residues in a furnace with a power of 100 kW and (4) the consideration of both electricity and steam coming from renewable resources. Considering these aspects, Fig. 3**B** is obtained, in which it could be observed that accounting for the renewability of both electricity and steam is the one that provides the best environmental improvement, with the exception of two impact categories, SOD and HNCT, in which it is observed a certain impact improvement, given the emissions derived from the combustion of wood for steam production.

Among renewable electricity or renewable steam, the assumption of the renewability of the electricity implies a lower environmental load, above all the impact categories of HCT and GW, in which the variation on reduction amounts to more than an 80 % in comparison. On the contrary, the lowest variation is observed on the SOD, GW, FRS, TA, FE and TET. Apart from that, it should be mentioned that no significant reduction is observed for any sensitivity proposed scenario for the impact categories of FE and ME, since in those categories the environmental benefit observed by the use of algae reduces significantly the impact loads that could be achieved by the energy requirements.

3.2.2. *Scenario 02. Ultrasound assisted extraction*

Table 2 shows the economic scores obtained for S02, considering the same assumptions as those defined for S01. In this case, the ultrafiltration unit is the largest contributor to the total equipment cost at $1071,118. An important advantage of this case study is that it does not use chemicals or enzymes, only water as the extraction solvent, which is reflected in the cost of materials, which only amounts to $33,265. However, this benefit is not reflected in the MSP obtained, which is higher than in the previous case, amounting to $12.62/g, since the extraction yield is significantly lower compared to S01, obtaining for S02 a total of 1.17 kg/batch of products compared to the value of 4.93 kg/batch of the S01 case. Nevertheless, S02 is also very profitable, with a positive NPV value and a payback of 4 years.

With respect to the LCA, the use of an emerging technology, as is the case in the UAE, has been shown to be beneficial in terms of chemical use. But, at the same time, as this type of extraction method is not optimized at industrial level, the amount of energy used is high, which implies a significant contribution to the environmental profile (Fig. 4**A**). Electricity is the main contributor in all the impact categories evaluated, except for the FE and ME impact categories, where the beneficial effects of the use of algae are observed, for the reasons mentioned in the previous scenario.

Since electricity is the main contributor, the sensitivity assessment was based solely on this element of the life cycle inventory. Two main scenarios were evaluated, one considering the reduction of electricity consumption by 20 % and the other considering the use of renewable

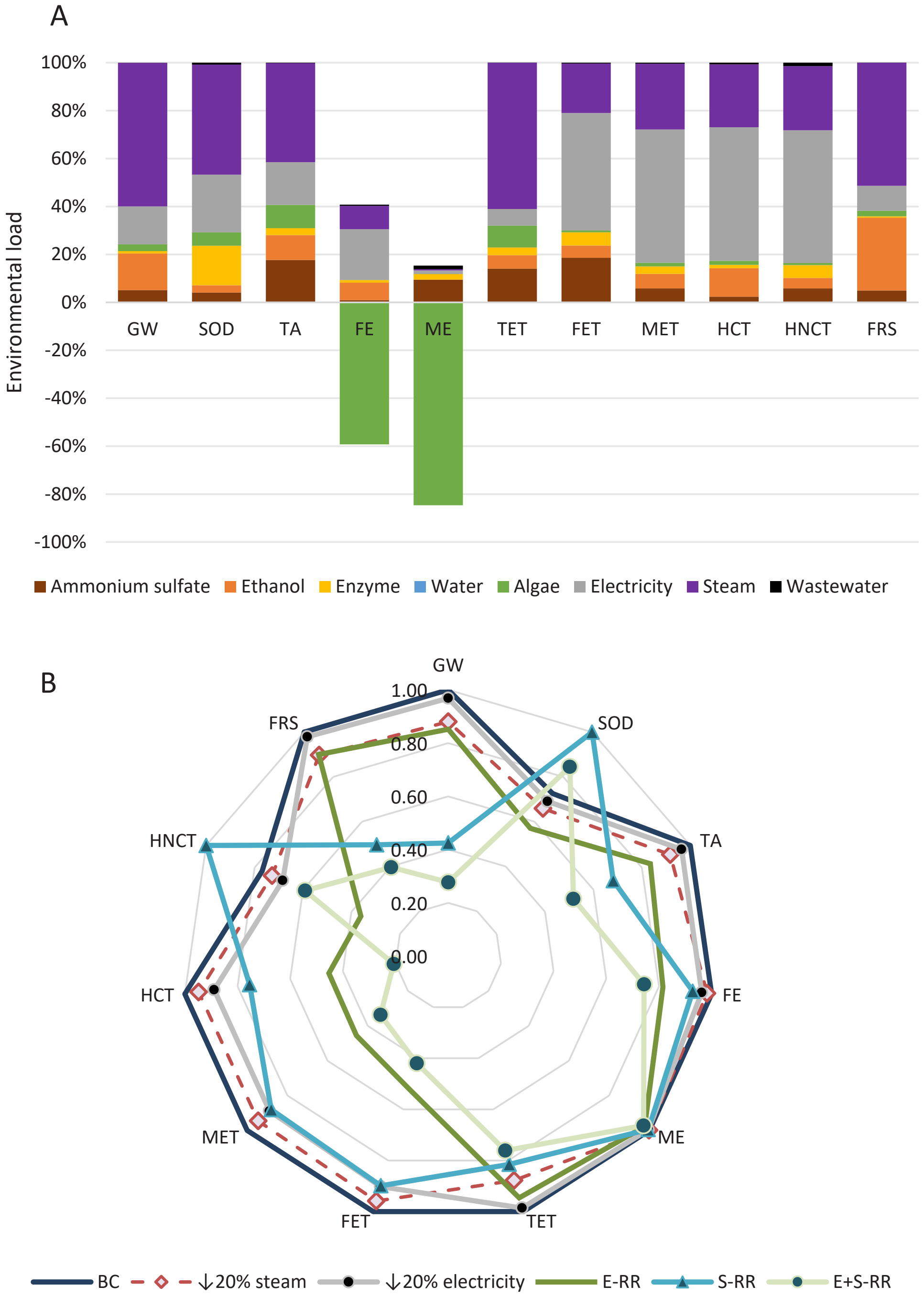


Fig. 3. (A) Environmental profile of the Scenario 01: water extraction and enzymatic digestion to obtain phycoerythrin and chlorophyll a. and (B) Sensitivity evaluation of the environmental profile of Scenario 01. Acronyms: BC (Base case), E-RR (electricity coming from renewable resources), S-RR (steam obtained using renewable resources) and E + S-RR (both electricity and steam renewable); GW (Global Warming), SOD (Stratospheric Ozone Depletion), TA (Terrestrial Acidification), FE (Freshwater Eutrophication), ME (Marine Eutrophication), TET (Terrestrial Ecotoxicity), FET (Freshwater Ecotoxicity), MET (Marine Ecotoxicity), HCT (Human Carcinogenic Toxicity), HNCT (Human Non-Carcinogenic Toxicity) and FRS (Fossil Resource Scarcity).

resources for its production. As expected, the use of non-fossil resources is the alternative that provides the greatest environmental benefit, with reductions ranging from of 52.6–96.5 %, except for the ME category, where only an 11 % reduction is observed (Fig. 4**B**). The reason behind this lies in the fact that, for this impact category, the main contributor, in this case a beneficial contributor, is the use of algae since the environmental load of electricity is less than 10 %. On the other hand, regarding the 20 % reduction of electricity needs, it implies an average reduction of 16.20 %, which is much lower than the 76.13 % achieved with renewable resources. Therefore, to improve the environmental profile of this alternative, the key is the use of renewable resources for energy production, along with trying to reduce energy requirements as much as possible.

3.2.3. Scenario 03. Enzymatic extraction

The equipment description as well as the economic results obtained for S03 are shown in Table 3. The total equipment cost is the lowest compared to the other scenarios; however, the extraction yield is the worst of the scenarios evaluated. The advantage in lower equipment costs is lost due to the very low productivity, as only 0.05 kg of product

Table 2
Techno-economic assessment results for Scenario 02. (1) The total equipment costs are updated to 2023 according to CEPCI INDEX.

Equipment	Capacity	Units	Purchase cost	Equipment	Capacity	Units	Purchase cost
Freeze Dryer	28.15 m^2	2	$90,155	Ultrafilter	65.61 m^2	2	$144,288
Grinder	42.21 kg/h	1	$14,121	Rotatory vc filter	2.46 m^2	1	$42,410
Spray dryer	665.84 L	1	$17,074	Hydrocyclone	0.7 m	1	$3210
Bioreactor	19.71 m^3	1	$43,982	**Total equipment cost ($) (1)**			**$1071,118**
Washer	252.5 kg/h	1	$26,333				

Item	Factor	Value
Direct costs		
Equipment delivered cost	1	$1071,118
Equipment erection	0.2	$214,224
Piping	0.1	$107,112
Instrumentation and controls	0.1	$107,112
Electrical	0.1	$107,112
Buildings	0.1	$107,112
Site preparation	0.1	$107,112
Total capital cost of installed equipment	**1.7**	**$1820,901**
Indirect costs		
Design, engineering and construction	0.4	$428,447
Contingency	0.2	$214,224
Total fixed capital costs	2.3	$2463,571
Working capital (15 % total capital cost)		$369,536
Total Capital Cost		**$2833,107**
Other costs		
Labor cost	-	$1353,909
Utilities cost	-	$105,721
Materials cost	-	$33,265
TEA SCORES		
Net present value	> 0	Profitable
Minimum selling Price	12.62 $/g	Lower than market average
Payback	4 years	Lower than Project lifetime

is obtained per process per batch, and this is also affecting the economic profitability of the process. The NPV obtained is negative and requires a minimum selling price significantly higher than the one considered as "base" (i.e. $108/g), and a return on investment higher than the expected lifetime of the project. To this end, it was concluded that S03 is not economically viable under these process conditions, requiring an increase the extraction efficiency of phycoerythrin and chlorophyll.

In terms of environmental assessment, in contrast to the previous environmental profiles obtained, the contribution of chemicals, specifically the use of sodium acetate pH buffer, is significant in almost all impact categories in Scenario 03 (Fig. 5**A**). The emissions related to its production process, together with the energy demand and chemical use are the main contributors to such a significant load. In this case, the contribution of steam is negligible in all impact categories, while some contribution from electricity is observed, with a maximum of 40 % in the FET and MET categories, and 60 % for HCT, with the lowest contribution of less than 15 % in the TA, FE and ME categories.

Given the environmental profile scores, the sensitivity assessment has been based on the 20 % reduction in the dose of sodium acetate required for pH control, 20 % reduction in electricity requirements from renewable resources. As can be seen in Fig. 5**B**, there is no significant difference in terms of reducing the sodium acetate dose or electricity needs by 20 %, the values achieved are barely equal for all the impact categories evaluated, except for TA and TET, for which a difference of about 10 % could be observed. On the contrary, the use of renewable energies really implies a significant improvement of the environmental loads obtained, with the exception of the impact categories in which the contribution of electricity on the base scenario profile is not significant, being the TA, FE, ME and TET. For the others, the range of reduction goes from 22.9 % for the SOD impact category to a maximum reduction of 49.9 % for the HCT, with an average reduction of 25.1 %.

3.2.4. Comparison between scenarios

The ReCiPe EndPoint methodology was used to determine which of the extraction alternatives is the most promising from an environmental perspective. As can be seen in Fig. 6**A**, the electricity required for the ultrasonic extraction method, Scenario 02, actually implies environmental damage on human health and ecosystems, the two categories in which this alternative is the worst. However, the water extraction method involving enzymatic digestion, Scenario 01, also has a significant damage potential, only 20 % lower than that of Scenario 02 in the ecosystems category, 35 % in the case of human health, but almost 60 % higher when assessing resource use. Among the three alternatives, Scenario 03 has the lowest damage potential.

On the other hand, since the assessment is based on a batch process, the amount of product that could be obtained for each alternative must also be considered. According to the data, Scenario 01 can produce 4.93 kg of product/batch, Scenario 02 is reduced to 1.17 kg/batch and Scenario 03 only 0.05 kg/batch. Given these important differences, it was considered to compare the extraction alternatives by selecting as the functional unit the amount of products obtained per batch. As expected, there is a huge difference between the values obtained, in fact the most promising scenario from the previous evaluation is now the worst, since it is the one with the lowest amount of products obtained (Fig. 6**B**). In this case, Scenario 01 is the most promising alternative from an environmental point of view.

Given this variation in the results, it was considered to evaluate the extraction strategies by means of sustainability and circularity indicators, available in bibliographic references and certification schemes, as well as the Greenness Grid methodology, based on the principles of Green Chemistry.

3.3. Applying environmental, social and circular indicators to the alternatives

Sustainable and circular aspects were selected according to certification schemes and official documents, such as the European Green Deal, the Circular Economy Action Plan or the ISCC (International Sustainability and Carbon Certification), and the ASC-MSC Seaweed Standard (which applies to sustainable and socially responsible seaweed production), among others [42].

The indicators considered for the assessment are those that best fit the available data, divided into three main pillars: environmental, social and circular indicators. The lack of data on the social pillar has meant

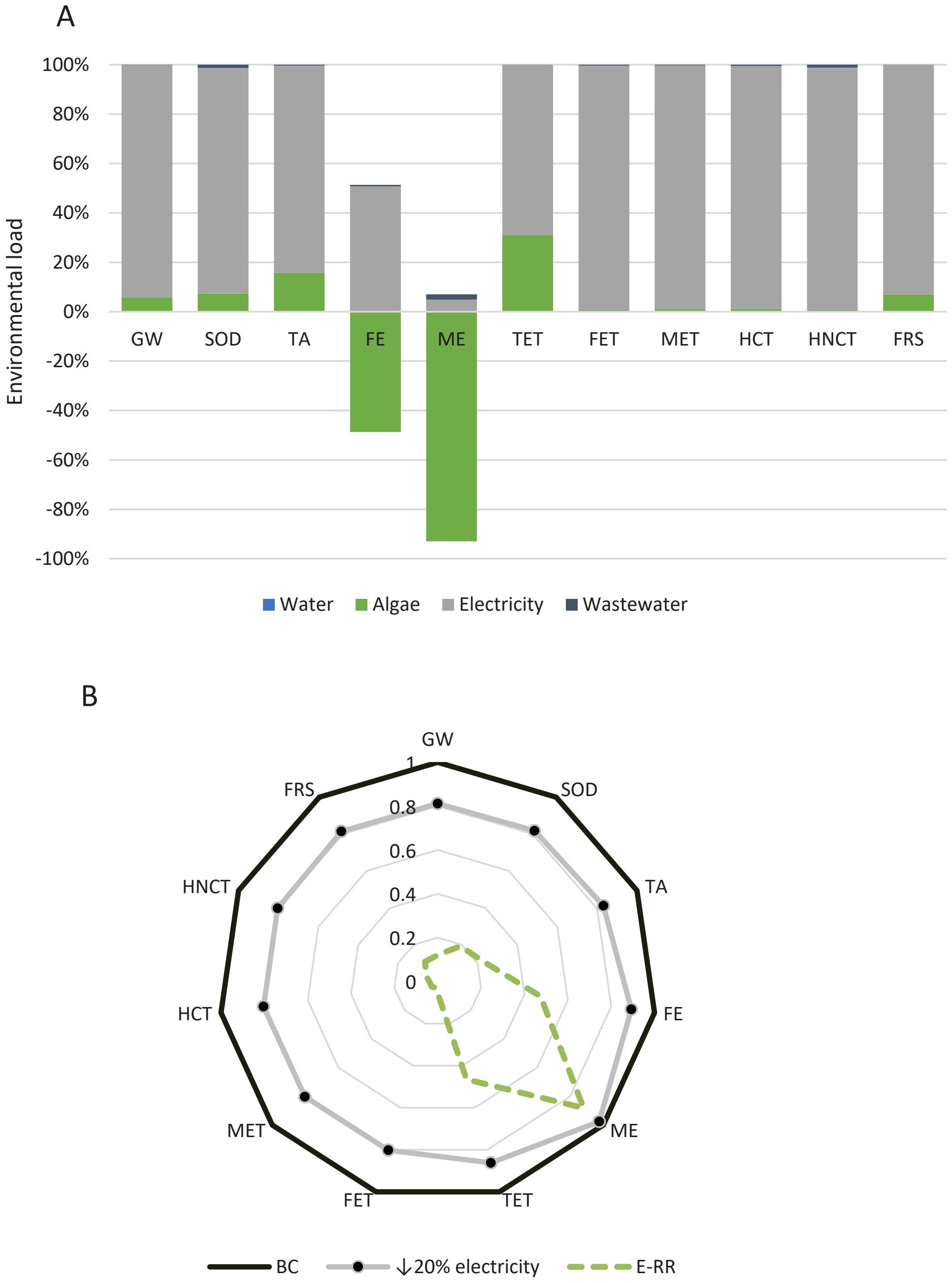


Fig. 4. (A) Environmental profile of the Scenario 02: UAE to obtain phycoerythrin and chlorophyll a and (B) Sensitivity evaluation of the environmental profile of Scenario 02. Acronyms: BC (Base case), E-RR (electricity coming from renewable resources); GW (Global Warming), SOD (Stratospheric Ozone Depletion), TA (Terrestrial Acidification), FE (Freshwater Eutrophication), ME (Marine Eutrophication), TET (Terrestrial Ecotoxicity), FET (Freshwater Ecotoxicity), MET (Marine Ecotoxicity), HCT (Human Carcinogenic Toxicity), HNCT (Human Non-Carcinogenic Toxicity) and FRS (Fossil Resource Scarcity).

that only three indicators could be scored, i.e., that of chemical consumption, which is related to the potential for harm on human health, and the implication on human carcinogenic and non-carcinogenic toxicity. On the other hand, in terms of circularity, three indicators have been included, one related to the recovery of chemicals or water at the facility, and another with respect to the amount of waste sent to landfill, which is related to the lack of more adequate management procedures, since sending them to landfill is not expected to result in recovery or valorization. The last one represents the productivity in the use of resources, which, in fact, is related to a circular performance: the more the integral use of resources is produced, the less waste is produced, thus promoting a greater circularity.

Furthermore, regarding the environmental pillar, it has been possible to analyze various indicators ranging from the quantification and evaluation of process-related emissions or efficiency in the use of energy, to the avoidance of waste effluents or water toxicity, among others. It is important to mention that these indicators have been calculated according to the data available from the process modelling through the SuperPro Designer tool and with the scores obtained from the development of the LCA methodology. On the other hand, another important fact is that the use of qualitative indicators was not contemplated, since this evaluation may be exposed to subjectivity, which could reduce the effectiveness in the selection of the most promising extraction alternative.

Table 4 shows the qualitative scores obtained by scenario and by type of indicator, with the best alternative in bold green and the worst

Table 3
Techno-economic assessment results for Scenario 03. (1) The total equipment costs are updated to 2023 according to CEPCI INDEX.

Equipment	Capacity	Units	Purchase cost	Equipment	Capacity	Units	Purchase cost
Freeze Dryer	28.15 m^2	2	$90,155	Ultrafilter	0.13 m^2	1	$1286
Grinder	42.21 kg/h	1	$14,121	Rotatory vc filter	0.95 m^2	1	$26,309
Centrifuge	12.42 kW	1	$18,350	Hydrocyclone	0.7 m	1	$3210
Bioreactor	7.61 m^3	1	$28,662	**Total equipment cost ($) (1)**			**$534,587**
Washer	252.5 kg/h	1	$26,312				

Item	**Factor**	**Value**
Direct costs		
Equipment delivered cost	1	$534,587
Equipment erection	0.2	$106,911
Piping	0.1	$53,459
Instrumentation and controls	0.1	$53,459
Electrical	0.1	$53,459
Buildings	0.1	$53,459
Site preparation	0.1	$53,459
Total capital cost of installed equipment	**1.7**	**$908,799**
Indirect costs		
Design, engineering and construction	0.4	$213,835
Contingency	0.2	$106,917
Total fixed capital costs	2.3	$1229,551
Working capital (15 % total capital cost)		$184,433
Total Capital Cost		**$1413,983**
Other costs		
Labor cost	-	$1353,909
Utilities cost	-	$15,171
Materials cost	-	$128,487
TEA SCORES		
Net present value	< 0	Not profitable
Minimum selling Price	82.35 $/g	Higher than market average
Payback	-	

alternative in red.

Scenario 01 is the most promising alternative in terms of the three indicators related to circularity, given that it achieves the greatest capacity for recovery of chemicals or water through the process, with a value of 12.26 tons/batch, significantly higher than that obtained by Scenario 03, which only achieves a score of 1.59 tons/batch. On the other hand, regarding waste sent to landfill, Scenario 01 presents the lowest amount of non-hazardous waste sent to landfill per kg of products obtained, with a score of 0.22, very similar to that of Scenario 02, which rises to 0.80, but significantly lower than that of Scenario 03, characterized with a score of 22.80. The reason for this high value of Scenario 03 is not the fact that a much larger amount of non-hazardous waste is produced compared to the other two scenarios, but its low production capacity, only 0.05 kg of products/batch, implies that this score increases significantly. Related to this is the "productivity over resource use" indicator, for which Scenario 01 is also the best, since it is the one with the highest mass of products per batch, 4.91 kg, compared to 1.17 and 0.05 obtained by Scenarios 02 and 03, respectively.

Regarding the social indicators, the most interesting results were obtained when evaluating the "Chemical Consumption" index, since the implementation of Scenario 02 implies a zero use of chemicals, thus obtaining a score of 0 for this indicator. On the other hand, given the low productivity of Scenario 03, together with the fact that it requires chemicals throughout the process, specifically sodium acetate to maintain the pH, which leads to a high value for this indicator. On the other hand, in terms of the two other social indicators, Scenario 01 is the most promising extraction alternative, since, on the one hand, a lower toxicity to human health per process per batch is achieved and, on the other hand, a higher amount of product per batch is obtained. Again, the low productivity of Scenario 03 is the reason behind the high carcinogenic potential per product obtained, thus making it the worst scenario.

Bearing in mind the environmental pillar, the scores obtained for "chemicals harmful to the ecosystem" and the two indicators based on "avoidance of water toxicity" are very similar between the scenarios, but, on the contrary, significant differences are observed when evaluating the wastewater produced and the water recovery along the process. For both cases, Scenario 01 is the one that provides the best score, while Scenario 03 is affected by its low productive productivity, given that these indicators are measured per kg of products obtained per batch process. As for the efficiency in the use of energy, it also depends on the productivity of the process, given this fact, even when Scenario 02 is developed, the amount of electricity required is higher, since the ultrasound assisted extraction is a very energy demanding technology, the ability to produce a higher amount of product per process per batch implies that Scenario 03 is the worst alternative with respect to this indicator and, once again, Scenario 01 provides the best score. Finally, considering the quantification of emissions, the absence of chemicals in Scenario 02 results in a significant advantage on this item, making this scenario the best, while Scenario 03 remains the least promising.

Therefore, according to the overall evaluation of the indicators, it can be determined that Scenario 01 seems to be the best alternative for most of the indicators assessed. Moreover, for those in which it does not achieve the best score, the differences with the other scenarios are not very significant, except for the "Chemical consumption" category in which, with a large difference, Scenario 02 is the best. On the contrary, the low efficiency of Scenario 03 marks it as the worst alternative in most of the indicators, since many of them are calculated based on the number of products obtained per batch. Therefore, improving the extraction yield would be the key to improving the sustainability and circularity of this recovery scenario.

3.4. Evaluation of the degree of sustainability using the Greenness Grid methodology

The main objective of Green Chemistry is to improve the reduction of environmental impacts resulting from the use of chemicals and the chemical-based process. It is based on 12 principles, in which C flows, energy efficiency, mass productivity, health and safety issues, as well as atom economy are some of the main aspects to be evaluated.

As can be seen in Table 5, the scenario that gets the highest green index, thus being the more sustainable, is S01, which is in line with the results obtained by the environmental analysis following the LCA methodology. Moreover, S03 also gets the worst value, being classified as a “on path to be sustainable” scenario, while both S01 and S02 get the

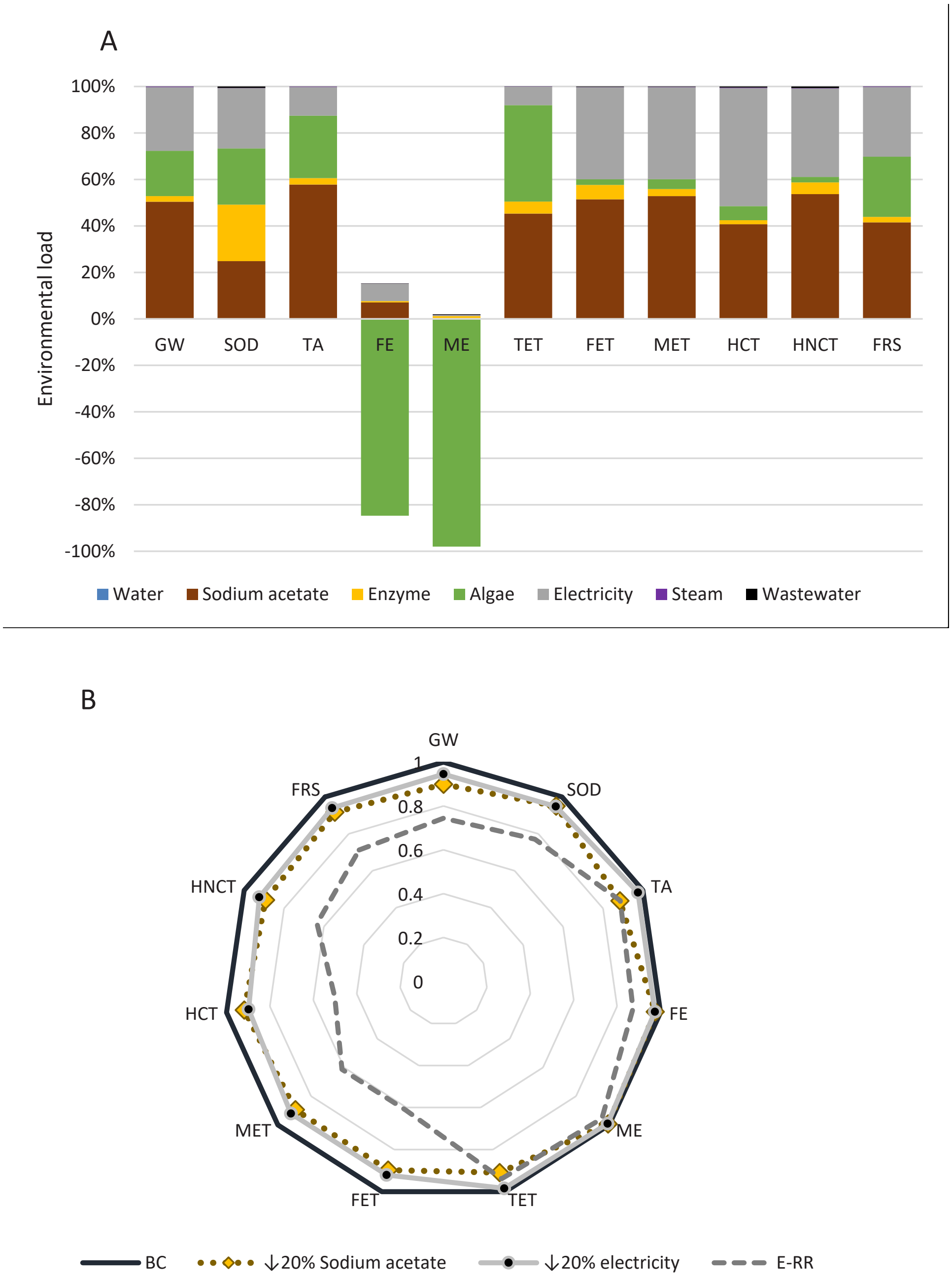


Fig. 5. (A) Environmental profile of the Scenario 03: enzymatic extraction to obtain phycoerythrin and (B) Sensitivity evaluation of the environmental profile of Scenario 03. Acronyms: BC (Base case), E-RR (electricity coming from renewable resources); GW (Global Warming), SOD (Stratospheric Ozone Depletion), TA (Terrestrial Acidification), FE (Freshwater Eutrophication), ME (Marine Eutrophication), TET (Terrestrial Ecotoxicity), FET (Freshwater Ecotoxicity), MET (Marine Ecotoxicity), HCT (Human Carcinogenic Toxicity), HNCT (Human Non-Carcinogenic Toxicity) and FRS (Fossil Resource Scarcity.

classification of "potential sustainable scenario". With respect to the individual scores obtained, the one in which a higher difference between the scenarios under evaluation is observed is for the one of "mass productivity", the principle 15, as it is the S01 the one that is more productive in terms of pigment production per amount of macroalgae used as input material. Looking to improve the scores achieved by applying the Greenness grid methodology, the increase on the energy efficiency, the enhancement of the atom economy, the improvement on the mass productivity of the process, as well as working on the prevention.

4. Conclusion

The main results of the development of the three calculation methodologies have demonstrated the potential of algae to be used as a natural resource for the extraction of phycoerythrin. The assessment of the profile associated with the harvesting, collection and transport of the algae has shown significantly lower environmental impacts than other marine species, thus demonstrating the suitability of using this natural resource as a raw material. However, going further in the life cycle stages, it has been found that the environmental impacts and sustainability potential are not analogous depending on the extraction process used. The use of emerging technologies, which are less optimized than conventional ones, fails in the efficient use of electricity, as in Scenario 02, where ultrasound-assisted extraction, for which not even chemical agents are required, does not achieve the best results given mainly the extensive use of electricity and the reduced production capacity

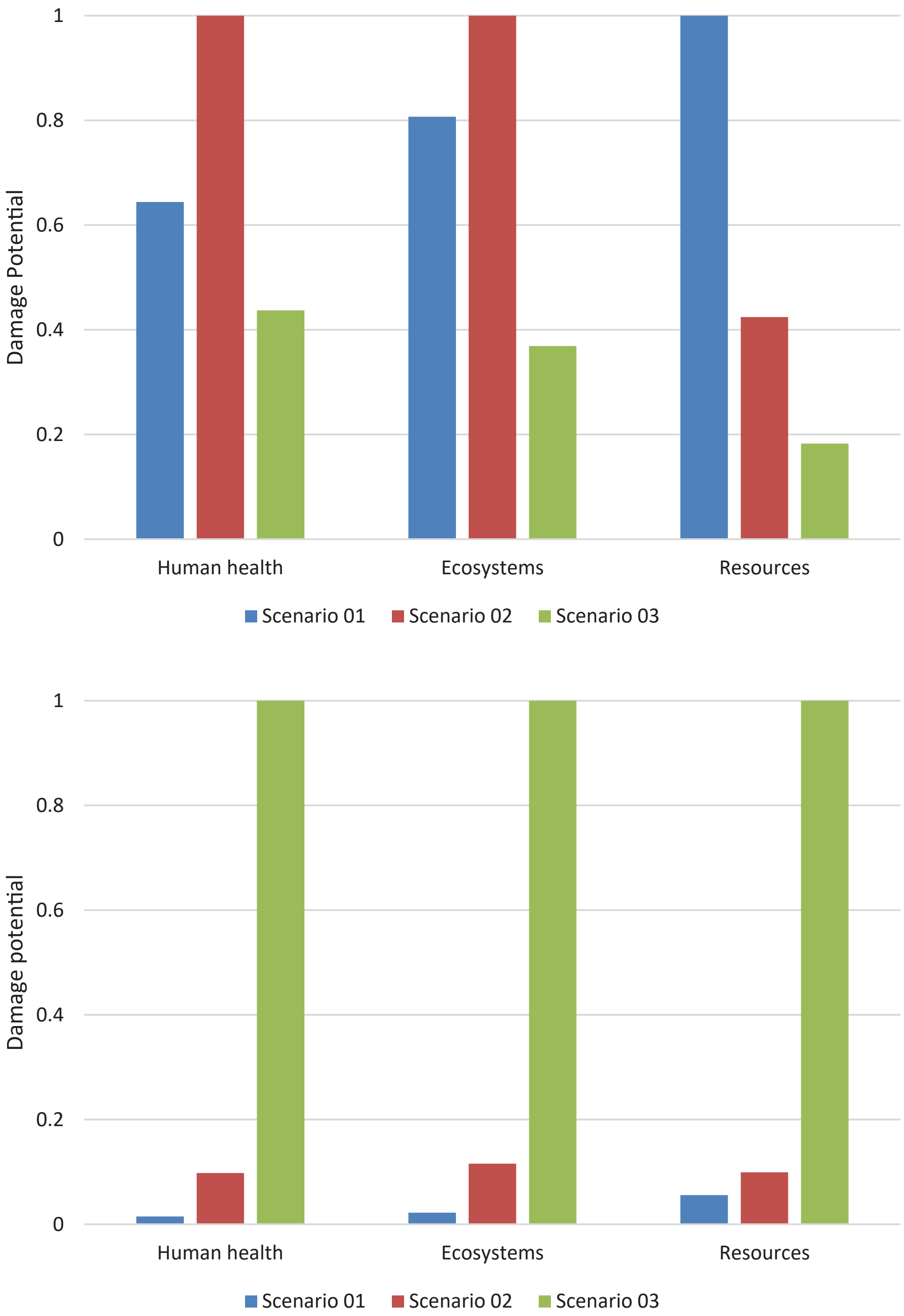


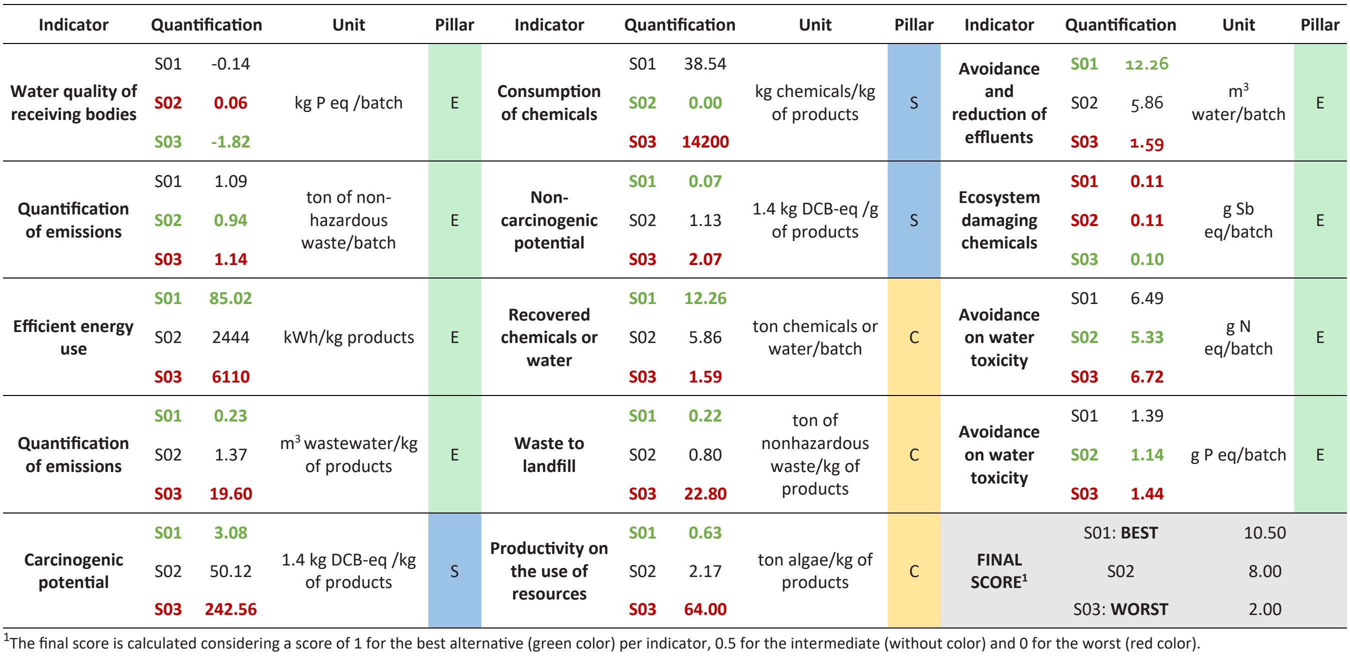
Fig. 6. (A) Comparison between the extraction scenarios by considering as functional unit 1 batch process and (B) comparison between the extraction scenarios by considering as functional unit the amount of products (in kg) obtained.

compared to that of Scenario 01, which is based on water extraction and enzymatic digestion. However, both scenarios have achieved sustainable scores and adequate circular indicators to be considered as potential extraction alternatives. On the contrary, Scenario 03, which uses an enzymatic reaction process, does not achieve such promising results, mainly given its low process productivity, since only 0.04 kg of products are obtained per process per batch, a very low value to be categorized as a feasible scenario. Moreover, this Scenario 03 is also not economically viable, while the other two extraction technologies evaluated have demonstrated their economic viability. On the other hand, according to the main contributors on environmental burdens, future algae valorization scenarios should advocate the use of renewable resources for energy requirements, mainly for the case of electricity, since greater environmental reductions are achieved by performing this sensitivity assessment. In addition, the use of emerging extraction technologies should also be encouraged, as they might be able to provide adequate production capacities, with reduced batch times and avoiding the use of chemicals, that are often harmful to the environment.

CRediT authorship contribution statement

Moreira Maria Teresa: Writing – review & editing, Validation,

Table 4
Environmental (E), social (S) and circular (C) indicators to evaluate the adequacy of the extraction alternatives. The value in green and bold represents the best alternative and the one in red and bold the worst.



Indicator	Quantification		Unit	Pillar	Indicator	Quantification		Unit	Pillar	Indicator	Quantification		Unit	Pillar
Water quality of receiving bodies	S01	-0.14	kg P eq /batch	E	**Consumption of chemicals**	S01	38.54	kg chemicals/kg of products	S	**Avoidance and reduction of effluents**	**S01**	**12.26**	m^3 water/batch	E
	S02	**0.06**				**S02**	**0.00**				S02	5.86		
	S03	**-1.82**				**S03**	**14200**				**S03**	**1.59**		
Quantification of emissions	S01	1.09	ton of non-hazardous waste/batch	E	**Non-carcinogenic potential**	**S01**	**0.07**	1.4 kg DCB-eq /g of products	S	**Ecosystem damaging chemicals**	**S01**	**0.11**	g Sb eq/batch	E
	S02	**0.94**				S02	1.13				**S02**	**0.11**		
	S03	**1.14**				**S03**	**2.07**				**S03**	**0.10**		
Efficient energy use	**S01**	**85.02**	kWh/kg products	E	**Recovered chemicals or water**	**S01**	**12.26**	ton chemicals or water/batch	C	**Avoidance on water toxicity**	S01	6.49	g N eq/batch	E
	S02	2444				S02	5.86				**S02**	**5.33**		
	S03	**6110**				**S03**	**1.59**				**S03**	**6.72**		
Quantification of emissions	**S01**	**0.23**	m^3 wastewater/kg of products	E	**Waste to landfill**	**S01**	**0.22**	ton of nonhazardous waste/kg of products	C	**Avoidance on water toxicity**	S01	1.39	g P eq/batch	E
	S02	1.37				S02	0.80				**S02**	**1.14**		
	S03	**19.60**				**S03**	**22.80**				**S03**	**1.44**		
Carcinogenic potential	**S01**	**3.08**	1.4 kg DCB-eq /kg of products	S	**Productivity on the use of resources**	**S01**	**0.63**	ton algae/kg of products	C	**FINAL SCORE**[1]	S01: **BEST**	10.50		
	S02	50.12				S02	2.17				S02	8.00		
	S03	**242.56**				**S03**	**64.00**				S03: **WORST**	2.00		

[1]The final score is calculated considering a score of 1 for the best alternative (green color) per indicator, 0.5 for the intermediate (without color) and 0 for the worst (red color).

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[1]The final score is calculated considering a score of 1 for the best alternative (green color) per indicator, 0.5 for the intermediate (without color) and 0 for the worst (red color).

Table 5
Scores obtained for the Green Index calculation per scenario.

Principle	S01	S02	S03	Principle	S01	S02	S03
1. Prevention	0.18	0.00	0.00	**9.** Catalysis	0.00	0.00	0.00
2. Atom economy	0.74	0.46	0.15	**10.** Degradation	1.00	1.00	1.00
3. Less hazardous	0.85	1.00	0.00	**11.** Pollution prevention	1.00	1.00	1.00
4. Safer chemicals	1.00	1.00	1.00	**12.** Accident prevention	0.70	1.00	1.00
5. Safer solvents	0.90	1.00	1.00	**13.** Carbon efficiency	1.00	1.00	1.00
6. Energy efficiency	0.50	0.50	0.50	**14.** Reaction efficiency	0.00	0.00	0.00
7. Renewable feedstocks	1.00	1.00	1.00	**15.** Mass productivity	0.60	0.06	0.00
8. Reduce derivatives	1.00	1.00	1.00	**GREEN INDEX**	**10.47**	**10.03**	**8.65**

Supervision, Conceptualization. **Romagnoli Francesco:** Writing – review & editing. **Paoli Riccardo:** Writing – review & editing. **Feijoo Gumersindo:** Writing – review & editing, Supervision. **Arias Ana:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis. **Ilmjärv Tanel:** Writing – review & editing, Supervision. **Entrena-Barbero Eduardo:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis.

Declaration of Competing Interest

none

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.nbt.2025.01.010.

Data availability

Data will be made available on request.

References

[1] Kotta J, Raudsepp U, Szava-Kovats R, Aps R, Armoskaite A, Barda I, et al. Assessing the potential for sea-based macroalgae cultivation and its application for nutrient removal in the Baltic Sea. Sci Total Environ 2022;839. https://doi.org/10.1016/j.scitotenv.2022.156230.

[2] Ahmed ZU, Hasan O, Rahman MM, Akter M, Rahman MS, Sarker S. Seaweeds for the sustainable blue economy development: A study from the south east coast of Bangladesh. Heliyon 2022;8. https://doi.org/10.1016/j.heliyon.2022.e09079.

[3] Auad G, Fath BD. Towards a flourishing blue economy: Identifying obstacles and pathways for its sustainable development. Curr Res Environ Sustain 2022;4. https://doi.org/10.1016/j.crsust.2022.100193.

[4] Spillias S, Cottrell RS, Kelly R, O'Brien KR, Adams J, Bellgrove A, et al. Expert perceptions of seaweed farming for sustainable development. J Clean Prod 2022; 368. https://doi.org/10.1016/j.jclepro.2022.133052.

[5] Duarte CM, Wu J, Xiao X, Bruhn A, Krause-Jensen D. Can seaweed farming play a role in climate change mitigation and adaptation? Front Mar Sci 2017;4. https://doi.org/10.3389/fmars.2017.00100.

[6] Qi L, Hu C, Barnes BB, Lapointe BE, Chen Y, Xie Y, et al. Climate and Anthropogenic Controls of Seaweed Expansions in the East China Sea and Yellow Sea. Geophys Res Lett 2022;49. https://doi.org/10.1029/2022GL098185.

[7] Jiménez-Escrig A, Gómez-Ordóñez E, Rupérez P. Seaweed as a source of novel nutraceuticals: Sulfated polysaccharides and peptides. Adv Food Nutr Res 2011;64. https://doi.org/10.1016/B978-0-12-387669-0.00026-0.

[8] Mahadevan K. Seaweeds: A sustainable food source. Seaweed Sustain: Food Non-Food Appl 2015. https://doi.org/10.1016/B978-0-12-418697-2.00013-1.

[9] del Río PG, Gomes-Dias JS, Rocha CMR, Romaní A, Garrote G, Domingues L. Recent trends on seaweed fractionation for liquid biofuels production. Bioresour Technol 2020;299. https://doi.org/10.1016/j.biortech.2019.122613.

[10] Theuerkauf SJ, Morris JA, Waters TJ, Wickliffe LC, Alleway HK, Jones RC. A global spatial analysis reveals where marine aquaculture can benefit nature and people. PLoS One 2019;14. https://doi.org/10.1371/journal.pone.0222282.

[11] Ytreberg E, Åström S, Fridell E. Valuating environmental impacts from ship emissions – The marine perspective. J Environ Manag 2021;282. https://doi.org/10.1016/j.jenvman.2021.111958.

[12] Vigouroux G, Kari E, Beltrán-Abaunza JM, Uotila P, Yuan D, Destouni G. Trend correlations for coastal eutrophication and its main local and whole-sea drivers – Application to the Baltic Sea. Sci Total Environ 2021;779. https://doi.org/10.1016/j.scitotenv.2021.146367.

[13] Desmit X, Thieu V, Billen G, Campuzano F, Dulière V, Garnier J, et al. Reducing marine eutrophication may require a paradigmatic change. Sci Total Environ 2018; 635. https://doi.org/10.1016/j.scitotenv.2018.04.181.

[14] Prasad Behera D, Vadodariya V, Veeragurunathan V, Sigamani S, Moovendhan M, Srinivasan R, et al. Seaweeds cultivation methods and their role in climate mitigation and environmental cleanup. Total Environ Res Themes 2022:3–4. https://doi.org/10.1016/j.totert.2022.100016.

[15] Hasselström L, Thomas JBE. A critical review of the life cycle climate impact in seaweed value chains to support carbon accounting and blue carbon financing. Clean Environ Syst 2022;6. https://doi.org/10.1016/j.cesys.2022.100093.

[16] Glasson CRK, Kinley RD, de Nys R, King N, Adams SL, Packer MA, et al. Benefits and risks of including the bromoform containing seaweed Asparagopsis in feed for the reduction of methane production from ruminants. Algal Res 2022;64. https://doi.org/10.1016/j.algal.2022.102673.

[17] Thomas JBE, Sodré Ribeiro M, Potting J, Cervin G, Nylund GM, Olsson J, et al. A comparative environmental life cycle assessment of hatchery, cultivation, and preservation of the kelp Saccharina latissima. ICES J Mar Sci 2021;78. https://doi.org/10.1093/icesjms/fsaa112.

[18] Chen Z, Wu W, Wen Y, Zhang L, Wu Y, Farid MS, et al. Recent advances of natural pigments from algae. Food Prod, Process Nutr 2023;5. https://doi.org/10.1186/s43014-023-00155-y.

[19] Kovaleski G, Kholany M, Dias LMS, Correia SFH, Ferreira RAS, Coutinho JAP, et al. Extraction and purification of phycobiliproteins from algae and their applications. Front Chem 2022;10. https://doi.org/10.3389/fchem.2022.1065355.

[20] Zhang Y, Yang T, Zhao X, Xin H, Liu D, Wang Q, et al. Comprehensive Analysis of Phycoerythrin 545 Stability and the Apoptotic Impact of Its Degradation Products on HT29 Cells. J Agric Food Chem 2024. https://doi.org/10.1021/ACS.JAFC.4C03808/ASSET/IMAGES/LARGE/JF4C03808_0004.JPEG.

[21] Rodak A, Stadlbauer K, Bobbili MR, Smrzka O, Rüker F, Wozniak Knopp G. Development of a Cytotoxic Antibody–Drug Conjugate Targeting Membrane Immunoglobulin E-Positive Cells. Int J Mol Sci 2023;24. https://doi.org/10.3390/ijms241914997.

[22] Ho ECH, Qiu R, Miller E, Bilotta MT, FitzGerald D, Antignani A. Antibody drug conjugates, targeting cancer-expressed EGFR, exhibit potent and specific antitumor activity. Biomed Pharmacother 2023;157. https://doi.org/10.1016/j.biopha.2022.114047.

[23] George R, John JA. Phycoerythrin as a potential natural colourant: A mini review. Int J Food Sci Technol 2023;58. https://doi.org/10.1111/ijfs.16229.

[24] Carmona R, Murillo MC, Lafarga T, Bermejo R. Assessment of the potential of microalgae-derived phycoerythrin as a natural colorant in beverages. J Appl Phycol 2022;34. https://doi.org/10.1007/s10811-022-02834-8.

[25] Sonani RR. Recent advances in production, purification and applications of phycobiliproteins. World J Biol Chem 2016;7. https://doi.org/10.4331/wjbc.v7.i1.100.

[26] Tan HT, Yusoff FM, Khaw YS, Noor Mazli NAI, Nazarudin MF, Shaharuddin NA, et al. A Review on a Hidden Gem: Phycoerythrin from Blue-Green Algae. Mar Drugs 2023;21. https://doi.org/10.3390/md21010028.

[27] Phycoerythrin Market Forecast to Reach USD 10.3 Million by 2034 with an 8.1% CAGR | Future Market Insights, Inc. – Market Research Blog n.d. https://marketresearchblog.org/2024/10/phycoerythrin-market-forecast-to-reach-usd-10–3-million-by-2034-with-an-8–1-cagr-future-market-insights-inc/ (accessed December 2, 2024).

[28] ISO. ISO 14040:2006. Environmental management - Life Cycle Assessment - Principles and Framework. 2009.

[29] Schaubroeck T. Hauschild MZ. Sustainability assessment of product systems in dire straits due to ISO 14040–14044 standards: Five key issues and solutions. J Ind Ecol 2022;26:1600–4. https://doi.org/10.1111/JIEC.13330.

[30] Anastas P, Eghbali N. Green Chemistry: Principles and Practice. Chem Soc Rev 2009;39:301–12. https://doi.org/10.1039/B918763B.

[31] Pinto J, Barroso T, Capitão-Mor J, Aguiar-Ricardo A. Towards a new, green and dynamic scoring tool, G2, to evaluate products and processes. J Clean Prod 2020; 276. https://doi.org/10.1016/j.jclepro.2020.123079.

[32] Vázquez-Rowe I, Hospido A, Moreira MT, Feijoo G. Best practices in life cycle assessment implementation in fisheries. Improving and broadening environmental assessment for seafood production systems. Trends Food Sci Technol 2012;28: 116–31. https://doi.org/10.1016/j.tifs.2012.07.003.

[33] EMEP/EEA. EMEP/EEA air pollutant emission inventory guidebook 2019: Technical guidance to prepare national emission inventories. Report No 13/2019. Luxembourg: Publications Office of the European Union. 2019.

[34] Hospido A, Tyedmers P. Life cycle environmental impacts of Spanish tuna fisheries. Fish Res 2005;76:174–86. https://doi.org/10.1016/j.fishres.2005.05.016.

[35] Lee D, Nishizawa M, Shimizu Y, Saeki H. Anti-inflammatory effects of dulse (Palmaria palmata) resulting from the simultaneous water-extraction of phycobiliproteins and chlorophyll a. Food Res Int 2017;100:514–21. https://doi.org/10.1016/J.FOODRES.2017.06.040.

[36] Titlyanov EA, Titlyanova TV, Kadel P, Lüning K. New methods of obtaining plantlets and tetraspores from fragments and cell aggregates of meristematic and submeristematic tissue of the red alga Palmaria palmata. J Exp Mar Biol Ecol 2006; 339:55–64. https://doi.org/10.1016/J.JEMBE.2006.07.014.

[37] Zuniga-Jara S, Soria-Barreto K, Godoy-Alfaro D. Economic valuation of the commercial aquaculture of Sarcopeltis skottsbergii in Southern Chile. J Appl Phycol 2022;34:2645–55. https://doi.org/10.1007/S10811-022-02710-5/FIGURES/14.

[38] Castro-Varela P, Celis-Pla PSM, Figueroa FL, Rubilar M. Highly Efficient Water-Based Extraction of Biliprotein R-Phycoerythrin From Marine the Red-Macroalga Sarcopeltis skottsbergii by Ultrasound and High-Pressure Homogenization Methods. Front Mar Sci 2022;9:988. https://doi.org/10.3389/FMARS.2022.877177/BIBTEX.

[39] Dumay J, Clément N, Morançais M, Fleurence J. Optimization of hydrolysis conditions of Palmaria palmata to enhance R-phycoerythrin extraction. Bioresour Technol 2013;131:21–7. https://doi.org/10.1016/J.BIORTECH.2012.12.146.

[40] de Lima EA, Mandelli F, Kolling D, Matsusato Souza J, de Oliveira Filho CA, Ribeiro da Silva M, et al. Development of an economically competitive Trichoderma-based platform for enzyme production: Bioprocess optimization, pilot plant scale-up, techno-economic analysis and life cycle assessment. Bioresour Technol 2022;364: 128019. https://doi.org/10.1016/J.BIORTECH.2022.128019.

[41] Langlois J, Sassi JF, Jard G, Steyer JP, Delgenes JP, Hélias A. Life cycle assessment of biomethane from offshore-cultivated seaweed. Biofuels, Bioprod Bioref 2012;6: 387–404. https://doi.org/10.1002/BBB.1330.

[42] report C.F.-E., 2020 undefined. The European green deal. EsdnEu 2020.