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Review

A Critical Review of Macroalgae Exploitation Pathways Implemented under the Scope of Life Cycle Assessment

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Abstract: Under the umbrella of Blue Economy, research interest is focused on harnessing the potential of macroalgae biomass, known as third-generation feedstock, from which multiple products can be extracted. As many of these exploitation pathways are not yet feasible for large-scale implementation, a significant number of publications adopt LCA as a tool to assess the sustainability of the proposed value chains. However, the complexity of such systems and the broad spectrum of alternative routes render a vague perspective on the sustainability of such applications. This study provides a critical review of previous research employing LCA to evaluate different pathways of macroalgae utilization. Ethanol, energy (biogas), and nutrition products were found to be among the most studied outputs in the past ten years from an LCA perspective. Different pathways leading to these products were mapped and analyzed, documenting their critical points and proposing measures to mitigate their environmental impact. A thorough SWOT analysis compiles for the first time the scattered information available in the literature, giving insights into the current state of macroalgae use and motives for further research. Insufficient or outdated inventory data for LCA, coupled with technical and technological struggles, were found to be the main barriers to large-scale applications.

Keywords: macroalgae; life cycle assessment; circular economy; biorefinery; SWOT

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1. Introduction

Increasing global needs for resources, coupled with the depletion of natural resources and the climate and energy crisis, have forced research to expand into various, previously unexplored, sectors [1,2]. Utilizing the immense yet untapped oceanic resources could be a start, minding that they currently provide only 2% of human food despite extending more than 70% of the Earth's surface [3]. Within this context, the Blue Economy has gained significant attention in recent years, referring to the development of economic activities for sustainable utilization of marine resources [4]. Under the umbrella of Blue Economy, recent research interest is focused on harnessing the potential of macroalgae biomass—known as third-generation feedstock—from which multiple products can be extracted. Although first- and second-generation fuels consume more energy than they yield, third-generation biofuels could, under conditions, achieve a positive energy balance [5,6].

Numerous products from macroalgae biomass have undergone research in recent years, exploring their application as raw materials for energy production or various products in the food, agricultural, pharmaceutical, and chemical industries. The range of these applications varies, just as the techniques for treatment and processing do, which can be determined to some extent by the algae species examined. All these different pathways enclose specific stages that stand out as energy hotspots, which have not been thoroughly studied, mainly due to the low technology readiness level. Most of these emerging technologies cannot yet be implemented on a large scale, and this is the reason why a significant number of publications adopt Life Cycle Analysis (LCA) as a tool to determine the sustainability of the proposed value chains. This study provides a critical review of previous

research employing the LCA methodology to evaluate different pathways of macroalgae utilization. In this context, the products found to be more frequently studied in the past ten years are outlined, presenting the different paths that can lead to them. Furthermore, documentation of the critical points of each pathway is conducted, along with proposed measures to mitigate their environmental impact.

The LCA of the entire biorefinery system allows industries to identify environmental hotspots within different seaweed valorization paths. These hotspots could refer to processes leading to intense energy consumption, such as electricity for drying, fermentation [7], or energy and heat demand for hydrolysis. It is crucial to highlight that not only are biorefinery processes energy consuming, but also the cultivation of the seaweed itself contributes to the total environmental impact [8]. Furthermore, the maintenance of offshore seaweed farms requires the use of fossil fuels, adding to the overall ecological footprint [9]. By identifying those hotspots, stakeholders could target directly into the core of the energy issue by adjusting the processes or incorporating renewable energy sources to reduce the dependence on conventional energy. Minimizing energy costs and the environmental footprint of seaweed biorefinery paves the way towards a more sustainable production chain aligned with the current needs for responsible production.

Seaweed exploitation can address many industries' needs, as their value chains have versatile applications in food, food additives, dietary supplements, animal feed, biostimulants (fertilizers), pharmaceuticals and nutraceuticals, bio packaging, carbon sequestration, and biofuel [10–13]. These applications can contribute to the implementation of several goals (SDGs) adopted by the United Nations in the context of the 2030 Agenda for Sustainable Development [14–18] (Figure 1). Regarding the goals in Table S1, the Europe Sustainable Development Report for 2023/24 presented the results of every country's performance against SDGs, showing that SGDs 2, 12, 13, 14, and 15 remain major challenges at the EU level, and goals 1, 3, 6, 7, and 11 also face challenges [19].

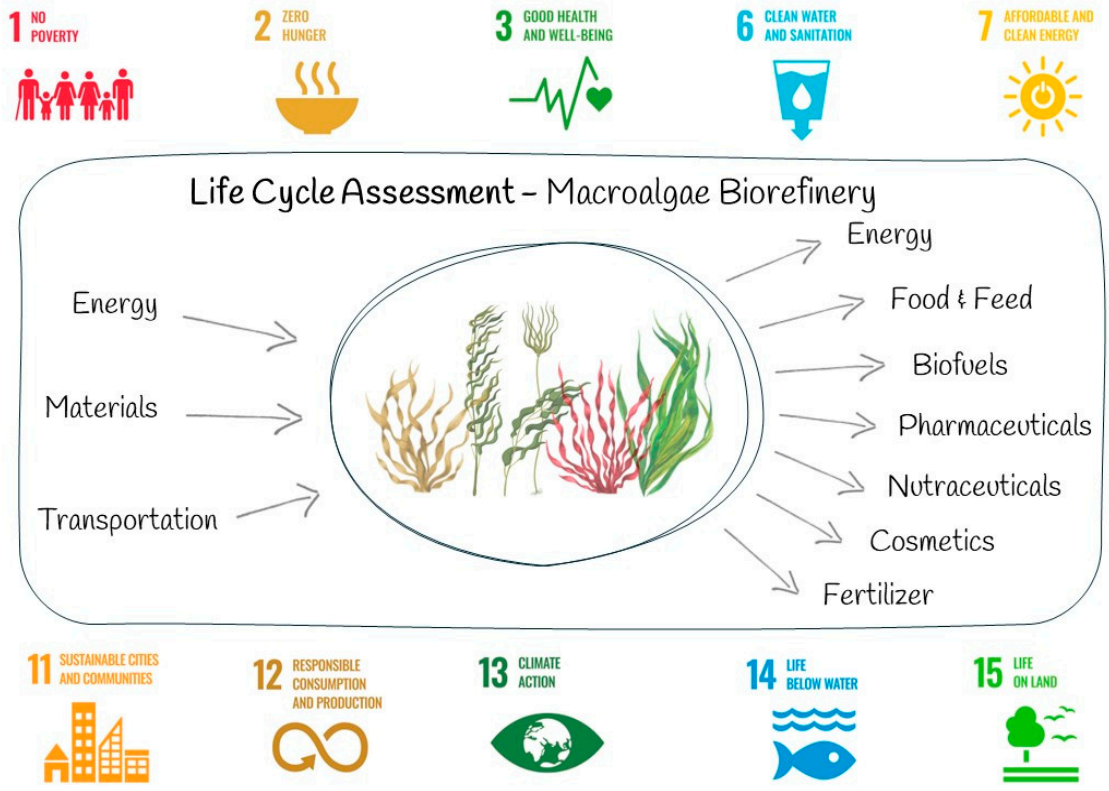

Figure 1. Products of macroalgae biorefinery contributing to Sustainable Development Goals.

In contrast to microalgae (phytoplankton), macroalgae, commonly known as seaweed, are multicellular eukaryotic organisms that undergo complex growing cycles in the aquatic environment. Depending on their composition (color) they are divided into three types: red macroalgae (Rodophyta), brown (Phaeophyta), and green (Chlorophyta), each category containing different polysaccharides [20]. The main components of seaweed biomass are polysaccharides, proteins, phenolic compounds, bioactive peptides, and pigments [21,22].

Asia accounted for 97.4% of the total worldwide seaweed production, dominated by China with the highest share (57%), followed by Indonesia (28%), and the Republic of Korea (5%) in 2019 [22]. Europe contributed 1.4% to the total macroalgae production, with Norway (0.46%), France (0.14%), and Ireland (0.08%) being among the primary producers, while Spain also has many macroalgae companies [23,24]. The shares coming from the other continents are relatively low. Regarding European macroalgae, a significant portion of the available biomass is distributed in the North Atlantic, with Saccharina emerging as the predominant seaweed group produced for the industry [25]. In the decade between 2012 and 2022, the total export value of EU seaweed for human consumption has raised over EUR 47 million, and Norway's mean harvested seaweed volume was 157 thousand metric tons annually (Figure S1). Figure S2 presents estimations of the commercial seaweed market in the United States, indicating that the market value will be higher than USD 1 billion in 2024 and the highest demand is anticipated in the food and pharmaceutical industries [26]. Strategic guidelines for EU aquaculture highlight the potential of seaweed cultivation as a low-footprint product on the European Green Deal challenges, and the guidelines share advice about using LCA methods to improve the performance of relevant practices in the aquaculture sector [27].

2. Materials and Methods

2.1. Life Cycle Analysis

Life cycle assessment (LCA) quantifies the overall resources consumed (materials and energy), emissions, and environmental and health impacts linked to any goods or services, considering the whole life cycle [28]. Therefore, LCA evaluates the environmental performance of products or services, helping to identify and prioritize improvement opportunities and compare different alternatives based on their environmental impact [29]. A typical LCA, in accordance with ISO 14040/44, consists of the following primary steps: (a) goal and scope and functional unit definition: defining the reason, the product, and the system; (b) life cycle inventory (LCI) phase: collecting and analyzing a system's input/output data; (c) life cycle impact assessment (LCIA): assessing the environmental significance; and (d) interpretation: discussion of the results, conclusions, and recommendations [30].

A "cradle-to-grave" methodology comprises a complete LCA from raw material production and/or extraction and its processing to products, use, and end-of-life/disposal. For instance, a "cradle-to-grave" methodology for a seaweed biorefinery that produces ethanol and biogas includes cultivation of seaweed, harvesting, transportation, conversion processes at the biorefinery, transportation of products, and their end use/disposal [31]. General environmental impact categories assessed are GWP100 expressed in kg CO_2, eq., acidification, terrestrial and freshwater ecotoxicity, water use, mineral and fossil resource scarcity, and human toxicity (carcinogenic and non-carcinogenic). LCA is usually assisted by software tools such as SimaPro and GaBi Pro, along with the use of LCI databases like Ecoinvent, Agribalyse, ELCD, etc. For the LCIA phase, LCA tools integrate methods for calculations of environmental categories such as ReCiPe2016, EF 3.0, CML-IA, etc. LCIA methodologies usually address impacts through midpoint or endpoint approaches. A midpoint approach focuses on short-term outcomes—for example, climate change impact—by estimating the increase in radiative forcing of CO_2, eq. On the contrary, an endpoint approach measures the ultimate consequences of environmental impacts, such as human lives lost, species extinction, and damage to resource availability [32]. With the results of the LCA, main environmental hotspots are identified, which can be further investigated in

search of alternative ways in order to optimize critical processes, increase product yields, and minimize environmental impact [33].

2.2. Methodology Analysis of This Work

The bibliography for this review was retrieved from the Scopus database. The main criteria on which publications were collected were (i) the reference to a detailed pathway of macroalgae utilization leading with one or more products; (ii) LCA was also conducted in the study. In other words, the aim was to map the documents that refer to final products from algae, presenting in detail all value chain stages while evaluating them for their environmental performance. The review covered the period of the last decade, i.e., from 2014 to 2024 (Table 1).

Algae can be referred to within a body of text with various terms, such as algae, macroalgae, seaweed or kelp. All these versions were included in the search input to ensure the accuracy of the final results. As an extra factor, the possibility that algal biomass might be mentioned nominally was considered, so three widely known genera of seaweed were added: *Laminaria* sp., *Saccharina* sp., and *Ulva* sp. The "*" symbol was used in the search section to cover all possible variations in a keyword's ending, e.g., the term "alga*" finds words like algae, algal, algae-based, etc. The search was conducted for article title, abstract, and keywords, using Boolean connectors: TITLE-ABS-KEY (("alga*" OR "macroalga*" OR "seaweed" OR "Saccharina" OR "Ulva") AND ("LCA" OR "Life Cycle Analysis" OR "Life Cycle Assessment") AND NOT "microalgae"). The last Boolean connector was used to exclude a significant portion of the literature about microalgae applications and products. The initial results of this reach were 508 publications. Defining the time frame between 2014–2024, the results number was reduced to 395. Choosing "article" as the document type led to 248 documents, while selecting "limited to all open access" resulted in 123 publications. Further screening was conducted following the primary purpose of the review, excluding publications without specific products, e.g., LCA of seaweed cultivation or any distinct description of the process steps. Although similar or general pathways leading to the same product were rejected, different inputs/feedstock (e.g., algae species) with similar treatment were considered separate pathways. Other factors that can distinguish similar paths are varied by-products that accompany the main ones and different cultivation techniques (e.g., onshore or offshore cultivation. After the screening, the final number is determined to be 23 publications. Critical processes acting as energy hotspots were singled out for 21 of these publications, as identified from their LCA results.

2.3. SWOT Analysis

The implementation of SWOT sheds light on the vague aspects of emerging scientific research, not only serving as a tool to review the current state of the examined technological sector, but also as a guide that highlights the challenging paths that need to be explored and improved by stakeholders to achieve sustainable development. SWOT analysis identifies the internal Strengths and Weaknesses and also the external Opportunities and Threats of the examined system. The extensive field of macroalgae applications should be examined and evaluated as a whole, regarding its prospects and limitations. In this way, the bigger picture can be formed about the feasibility of the larger scale macroalgae exploitation by the industry.

3. Results

The methodology followed to identify and write down macroalgae utilization pathways from a recent bibliography is described above. Figures 2–4 show the final products with the most references in publications conducting LCA in macroalgae-derived products. These products are ethanol, energy, and a basket of food sector products.

(i) Ethanol production

Typical processes for ethanol production include hydrolyzation of polysaccharides to simple sugars, fermentation to bioethanol, and distillation to recover the final product [34,35].

Five pathways for ethanol production are demonstrated in Figure 2. Brockmann et al. [36] analysed three different cultivation methods of green macroalgae *Ulva* sp. as a feedstock for ethanol production. Path (a) shows the different cultivation scenarios: harvesting in raceway systems, integration of seaweed culture into fish farms and offshore harvest. The biorefinery consists of four processes: hydrolysis, fermentation, distillation, and purification. Outputs of the distillation process are cattle feed and ethanol, with the latter directed to the purification unit. Golberg et. at [37] introduced the concept of a hybrid biorefinery with dual input of seaweed and solar energy, as shown in the path (b): Offshore cultivated green seaweed *Ulva* sp. It goes through pretreatment before entering a hydrothermal reactor, which is powered with thermal energy by a parabolic trough solar collector. The reactor's output is separated into two different streams: a flash and a solid–liquid stream. The solids from the latter stream get separated for the recovery of the solid tank to produce ethanol. Co-products of this process are solid hydrochar, proteins and electricity generated from a steam turbine that utilizes the steam generated from the collector. Fasahati et al. [31] examined two different biological conversion pathways to produce ethanol from brown macroalgae; sugar and VFAs pathway (paths (c) and (d) in Figure 2). In pathway (c), the carbohydrate content of offshore cultivated brown macroalgae L. japonica undergoes enzymatic hydrolysis and then proceeds to the fermentation unit, followed by the ethanol recovery unit. The recovery unit uses a beer column, distillation column, and permeation membranes. The by-product of this process is fertilizer, originating from the solids separated in the beer column and then subsequently drained in a press filter. The main product of the VFAs pathway (d) is ethanol and heavier alcohols (propanol and butanol). In this case, partial anaerobic digestion is employed using inhibitors, to hinder the full breakdown of VFAs during the digestion process. VFAs content from the liquid stream is extracted with methyl-butyl ether (MTBE) in the extraction column, followed by distillation columns. The hydrogenation unit receives the recovered VFAs and gas-phase catalytic hydrogenation is conducted at 290 °C and 60 atm to produce ethanol along with propanol and butanol. The solid fraction of partial AD is filtered and distributed as fertilizer. Seghetta et al. [38] implemented LCA methodology for offshore cultivated brown macroalgae *S. latissima* and *L. digitata*. Path (e) presents partially dried seaweed biomass to be transferred to the biorefinery unit, where hydrolysis and fermentation take place sequentially. After SLS, the fermentation broth is divided into solid and liquid streams; the solid phase undergoes spray drying to produce protein-rich fish feed ingredients, while the liquid stream enters a distillation unit to recover ethanol and liquid fertilizer. LCAs utilized in research have identified the ability of such biorefinery systems to mitigate climate change. In the case of [31], ethanol production via fermentation was the best alternative for energy production compared to VFAs and energy production through biogas produced from the anaerobic digestion of seaweed. However, culture systems, primarily drying processes, contributed the most to environmental burdens in all cases due to the amount of energy [36] and/or fossil fuel they require.

All five pathways for ethanol production used a "cradle-to-grave" approach to assess the environmental performance. Three out of five pathways use as functional unit 1 ton of dried seaweed, while the others are considered as functional unit a basket of products derived from 1 ton of dry seaweed and 1 ha of sea cultivated. Except for path a), all pathways refer to offshore seaweed cultivation and examine green (*Ulva* sp.) and brown (*L. japonica*, *L. digitata* and *S. latissima*) macroalgae species. Regarding transport, in path a) the harvested seaweed is transported by lorry to the fermentation plant, path (b) examines different scenarios for road (truck) and rail transport, paths (c) and (d) investigate wet and dry transportation by boat and truck, while path (e) describes transport by boat followed by lorry for dry seaweed biomass. All LCAs were conducted with the SimaPro software.

(ii) Biogas production

Given its technology maturity, anaerobic digestion is widely recognized as a promising method for biofuel production from macroalgae biomass [39]. Figure 3 demonstrates six macroalgae utilization pathways found in the bibliography with biogas as the end product (i.e., energy). In each pathway, the solid fraction of anaerobic digestion is used as fertilizer,

addressing the challenge of effective digestate utilization [40]. Fasahati et al. also described a methane pathway for heat and energy production using the brown seaweed *L. japonica* biomass, shown as path (a) in Figure 3 [31]. In path (b), Seghetta et al. demonstrated a biogas production pathway from *L. digitata* and *S. latissima* biomass utilization [41]. They incorporated in their LCA different scenarios of macroalgae biomass storage, partial drying or seaweed ensilage. The biogas generated from AD is sent to a co-generation engine (CHP) for energy production. Pathways (c) and (d) examine the co-digestion of algae with agricultural and farm waste. Cappelli et al. investigated the sustainability of co-digesting green seaweed *Ulva lactuca* with agricultural waste (i.e., chicken manure, oil mill waste waters, and citrus pulp) for biogas production in an actual pilot plant [42]. The system integrates a CHP unit generating heat and electricity from biogas, while the solid fraction of the digestate is distributed as fertilizer, as displayed in path (c). In pathway (d) Ertem et al. assessed the co-digestion of a macroalgal mixture of red and brown seaweed with farm waste (i.e., corn, grass, rye, and poultry manure) in an industrial-scale biogas plant [43]. Nilsson et al. described a biorefinery setup utilizing *S. latissima* biomass for co-production of biogas, fertilizer, biomaterials, and sodium alginate [44]. As visualized in path (e), dry *S. digitata* biomass proceeds to acid pretreatment and then conventional and ultrasound-assisted methods are employed for sodium alginate extraction. The lignocellulosic fraction is used for biodegradable material production, while sodium alginate is recovered by conducting convective drying to the precipitate. Path (f) refers to LCA conducted by Czyrnek-Delêtre et al., assessing the sustainability of biogas production from an integrated macroalgae and salmon farm in Ireland [45]. Pressure swing adsorption (PSA) is employed for biogas upgrading, occurring prior to the biogas entering a compressor to give compressed biomethane as the final product.

Pathways for energy production tend to be similar, with biogas, heat, and fertilizer as common system outputs. Path (a) is a cradle-to-grave assessment with a functional unit of 1 ton of dry seaweed. This path involves offshore cultivation of brown macroalgae, exploring different scenarios for wet or dry biomass transportation. The employed functional unit in path (b) is 1 ha of offshore cultivation area and combines two brown seaweed species: *S. latissima* and *L. digitata*. It includes water transport from cultivation sites to harbour followed by road transport of partially dried biomass. Like the first path, path (c) also uses cradle-to-grave LCA, but in this case, the macroalgae (*Ulva lactuca*) are cultivated onshore. On-site macroalgae practically minimizes the environmental impacts of seaweed transportation. The functional unit of this LCA is 1 m^3 of biogas produced. Unlike other paths, path (d) proposes co-digestion of brown and red macroalgae with farm waste, although the seaweed species are not specified. Two functional units are set: 1 kg of feedstock mixture fed into the digester and 1 MJ of energy production from biogas. In this path, algae transportation is conducted by car. Pathways (e) and (f) focus on offshore cultivation of brown macroalgae Saccharina latissima and Laminaria digitata, respectively. Path (e) is the only case of gate-to-gate LCA, also using two functional units: 1 kg of sodium alginate and 1 ton of dry biomass. Transportation in path (e) is carried out by lorry. Path (f) applies an attributional approach in cradle-to-gate LCA, considering as functional unit 1 MJ of compressed biomethane. Tankers are used for road transport. All LCAs examined in Figure 3—except pathway (f)—were implemented in SimaPro software. Czyrnek-Delêtre et al. for path (f) used the Gabi software.

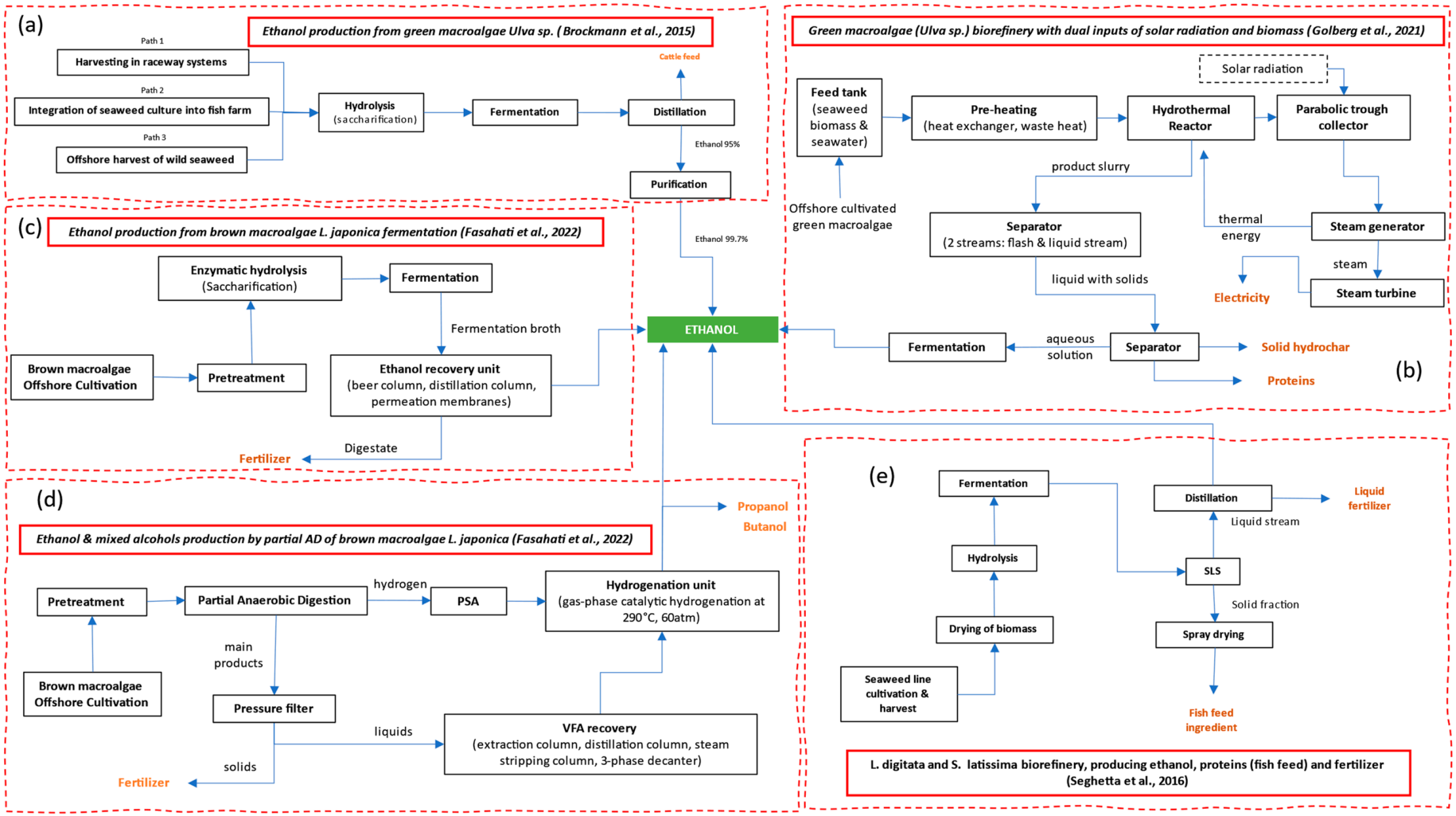

Figure 2. Different macroalgae utilization strategies for ethanol production: (**a**) [29], (**b**) [30], (**c**) [24] (**d**), [24], (**e**) [31].

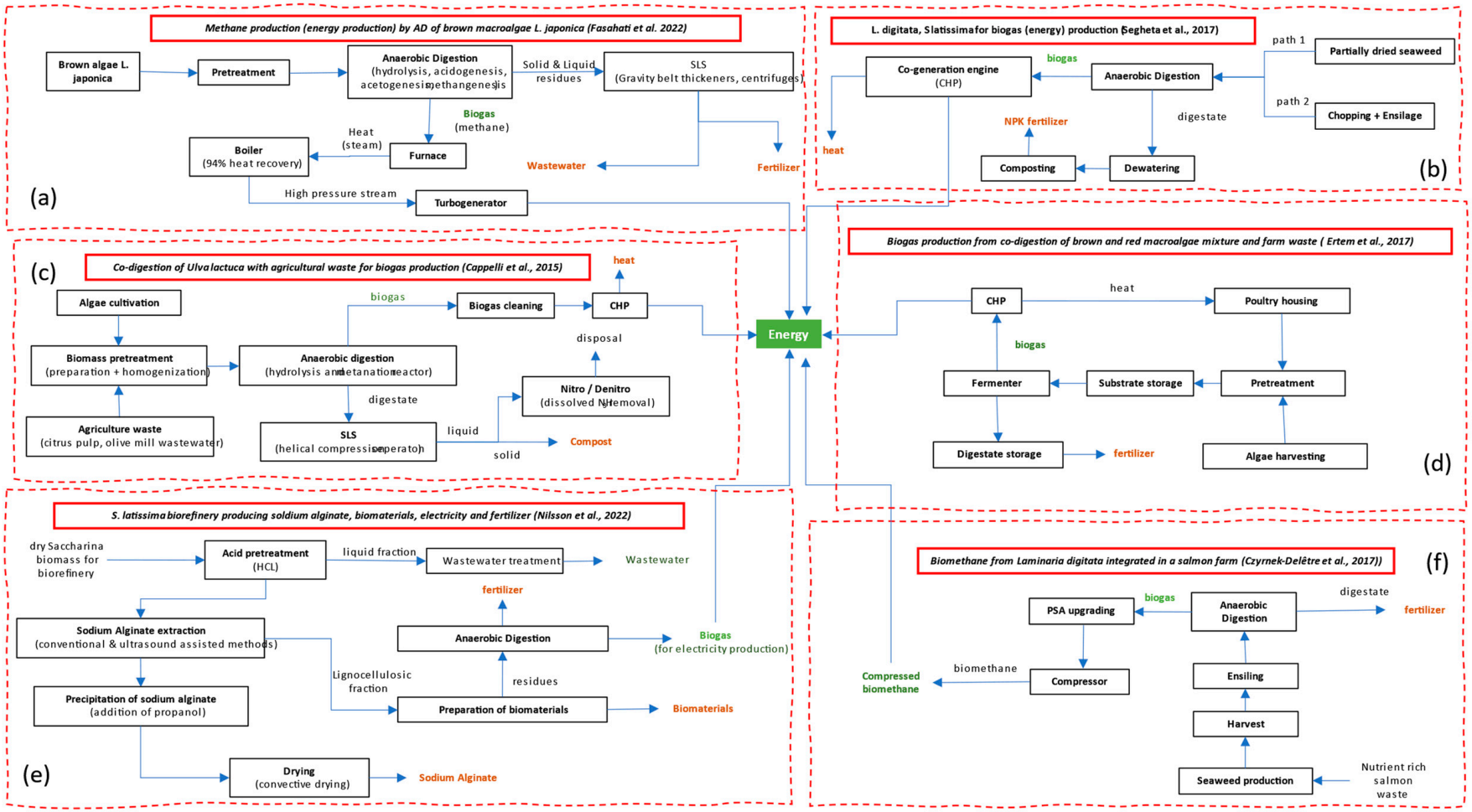

Figure 3. Energy production as potential outcome of different macroalgae valorization techniques: (**a**) [24], (**b**) [34], (**c**) [35], (**d**) [36], (**e**) [37], (**f**) [38].

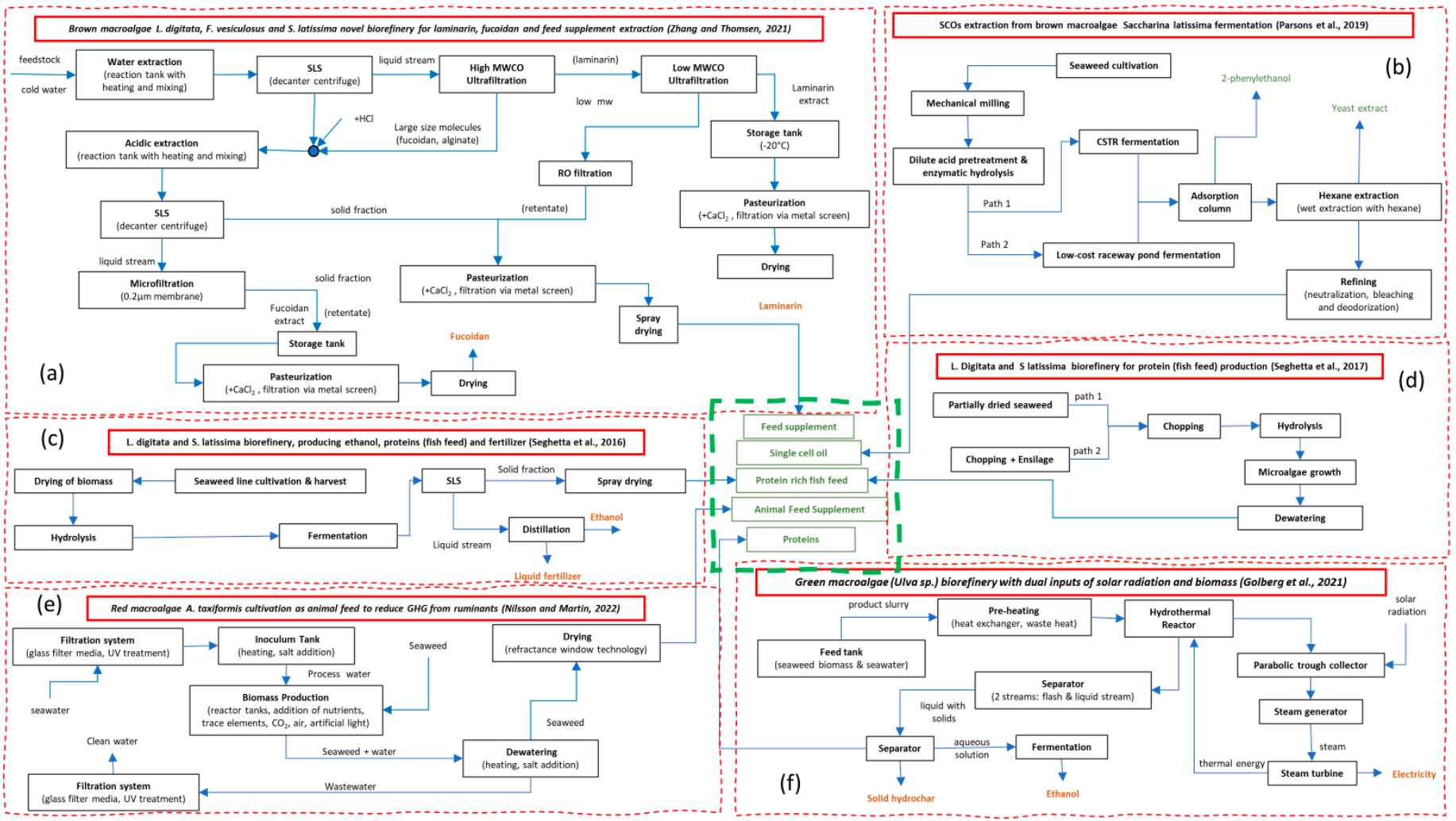

Figure 4. Nutrition products derived from different macroalgae exploitation pathways: (**a**) [42], (**b**) [45], (**c**) [31], (**d**) [34], (**e**) [40], (**f**) [30].

Table 1. Typology of the selected papers based on the environmentally critical processes of their processing pathway.

Path	Main Product	Critical Process	Description	Potential Greening Solutions
Fermentation of brown macroalgae to produce ethanol [31].	ethanol	**Ethanol recovery** (82%), fermentation area (13.4%).	Steam for distillation and power for refrigeration to condense the permeates of pervaporation membranes, make the recovery of ethanol the main hotspot. Fermentation emerges as second hotspot, due to the requirement for hot water wash and agitation.	Solar thermal systems for preheating [46] (fermentation, distillation) solar electricity (membrane separation, sieve adsorption, freeze separation, extraction), and thermal integration of streams
Partial anaerobic digestion of brown macroalgae to produce ethanol and heavier alcohols [31].	ethanol and heavier alcohols	**VFA recovery (53%)**, hydrogenation (23%), fermentation (11%), and alcohol recovery (10%) accounted for the majority of the energy consumed.	Low VFA concentration requires high MTBE-to-VFA loading ratio, resulting in significant increase of the separation equipment and energy required for MTBE recovery.	Solar thermal systems for preheating (fermentation, distillation), solar electricity (membrane separation, sieve adsorption, freeze separation, extraction)
Anaerobic digestion of brown macroalgae exploitation to produce heat and power [31].	heat and power	Very low energy requirement, mostly consumed by digesters and cooling water to condense vapours.	This pathway supplies all its energy demands with a fraction of the heat and electricity produced by the boiler and turbogenerator.	(The process produces green heat and power)
Asparagopsis taxiformis **cultivation** for animal feed [47]	feed supplement	**Inoculum tank** (64% of the total GHG emissions), **Biomass production** (33% of the total GHG emissions).	The salt input for inoculum tank accounted for 48% of the total GHG emissions from the system. Emissions were also impacted by the large amount of thermal energy utilized.	Using less salt by increasing the water recycling rate; Use of other salt sources; solar electricity for illumination and the material input of biomass reactors; solar heat for combined heating
Saccharina latissima cultivation and biorefinery for production of food, biomaterials and energy [44]	sodium alginate, biogas, biomaterials, fertilizer	**Drying** contributed to 38–95% of total impacts. **Boat fuel** for farm maintenance was the second largest climate hot spot. The process of **extracting alginate** gives the single largest contribution to the overall impacts.	Drying of biomass for post-harvest preservation and fuel use were the main hotspots in the cultivation phase. Drying accounted for 75% of the climate impact. For alginate extraction, the yield and purification were the major energy consumers.	Solar drying of seaweed; green fuels (biofuels, e-fuels) for boats' movement; solar electricity for purification processes

Table 1. *Cont.*

Path	Main Product	Critical Process	Description	Potential Greening Solutions
Ulva sp. Biorefinery with dual inputs of solar radiation and biomass [37]	hydrochar, elecctricity, protein, ethanol	**Cultivation** (mixing and aeration), **transport**.	Most impacts stem from electricity consumption during cultivation, including mixing and aeration. A smaller fraction of the impact arises from biomass transport and brine. In certain categories, like climate change, the hotspot shifts to transportation.	Green fuels (biofuels, e-fuels) for boat transfer; solar electricity for cultivation solar thermal systems for preheating; (fermentation, distillation) [46] solar electricity (membrane separation, sieve adsorption, freeze separation, extraction) thermal integration of thermal streams
Sequential extraction of laminarin, fucoidan and alginate from brown macroalgae Ecklonia maxima [48].	alginate, laminarin, fucoidan	Major energy hotspots across systems are the heating for the **extraction process** and **product drying**.	In the REF system, oven drying of alginate contributes to 23% of the total electricity use, while extraction heating energy demand accounts for 68% of the system-level electricity. In SWE and HWE systems, oven drying and spray drying account for 61% and 77% of the total electricity consumption.	Solar drying of alginates; solar heat for extraction; solar electricity for all processing
Brown seaweed (*Laminaria digitata*, *Fucus vesiculosus*, *Saccharina latissima*) biorefinery, for Laminarin, fucoidan and feed supplement production [49].	Laminarin, Fucoidan, Feed supplement	Onsite energy consumption for **product drying** and **process heating** and the upstream energy use for **membrane manufacturing** dominate the system-level carbon footprints, with a respective share of 37–70% and 8–61%.	**Pilot scale:** Spray drying is the major hotspot in all pilot scale systems, accounting for 63–70% of the system-level GWP. **Industrial scale**: major contributions to GWP come from Reverse Osmosis membrane (41–47%), water extraction process and ultrafiltration (23–29%), and spray drying (11–15%).	Solar drying of seaweed solar heat for processes solar electricity for reverse osmosis thermal integration of streams

Table 1. *Cont.*

Path	Main Product	Critical Process	Description	Potential Greening Solutions
Gracilaria edulis cultivation and processing to produce plant biostimulant [50].	plant biostimulant	**Processing** contributed to a higher proportion of impacts across different categories. Plastics in **packaging** of the extract and the amount used in cultivation contributed to more than 50% of impacts across 8 out of the 19 categories.	Electricity requirement, shed and blowmoulding sub-processess within the processing step contributed to the bulk of the evaluated environmental impact categories.	solar heat for processes solar electricity for processes bioplastics use reused and recycled plastics
Lactic acid production from *Laminaria* sp. [51].	lactic acid	**Drying**	Energy for drying prior to fermentation process is the main driver of global warming impact results.	solar drying for *Laminaria* sp. solar heat for processing
Production of Single–cell oils from Saccharina latissima fermentation [52].	SCOs	**Fermentation** and **acid pretreatment and enzymatic hydrolysis** contributed to the most impact categories assessed. **Cultivation** is the third most dominant hotspot.	Electricity for fermentation, and electricity and heat (steam) for hydrolysis where the main sources of energy consumption. Cultivation adds to the total climate change impact, due to electricity required in nursery stage.	solar heat for fermentation solar electricity for all processes
Experimental Production of Lactic Acid for Bioplastics from *Ulva* spp. [53]	lactic acid	Electricity use is dominant in climate change impacts. The main hotspot is derived from electricity needs in cultivation.	99% of the electricity consumption occurs during pumping and aeration for cultivation. Hydrolysis is a secondary hotspot due to CO_2 emissions.	high-efficiency pumps solar electricity for all processes
Biomethane from *Laminaria digitata* digestion [45].	biogas, fertilizer	**Digestate handling, storage**, and **field application**, is the largest contributor in all impact categories.		(The process produces green heat and power)
S. latissima and *L. digitata*: (i) Offshore cultivation, (ii) biogas and (iii) protein production pathways [41].	biogas, protein, electricity	**Cultivation** is the most energy-intensive process in all scenarios (58–89%). **Drying** is also contributing to 56–73% of energy consumption, while **dewatering** has a notable impact in the protein production pathway.	Production of cultivation lines materials render this process as energy hotspot. For protein production, electricity for dewatering has a major contribution.	solar drying of seaweed solar heat for cultivation solar electricity for separation of water

Table 1. *Cont.*

Path	Main Product	Critical Process	Description	Potential Greening Solutions
S. latissima cultivation [8]	*Saccharina* sp. biomass	The most important impacts came from **drying** the harvested seaweed, and from the **production** of the **chromium steel chains** and **polypropylene rope** in the infrastructure.	Drying makes a major contribution to the most categories.	solar drying of seaweed solar heat for processes solar electricity for the production of steel chains
Extraction of essential (terpene) oils from *Ochtodes Secundiramea* cultivated in photobioreactor (PBR) [54].	essential oils	Cultivation in the photobioreactor is the main cause of the high energy requirements, with 86% of the total electricity consumption.	Electricity for PBR illumination reflects to 81% of the total energy consumption. Production of chemicals for extraction poses the most significant challenges in terms of ODP (97%), due to the use of dichloromethane as a solvent.	solar heat for processing solar electricity for bioprocessing energy efficient lighting [6]
Saccharina sp. offshore production [55].	*Saccharina* sp. biomass	**Nursery** phase	Electricity—air pump, water pump, sand filter, UV filter.	high-efficiency pumps solar drying of *Saccharina* sp. solar electricity for processes
Laminaria digitata and *Saccharina latissima* biorefinery, producing ethanol, proteins (fish feed) and fertilizer [38].	ethanol, proteins (fish feed), fertilizer	**Drying** (63% of the energy used), followed by the **cultivation** (28%).	Drying process seems to be the major energy consumer; however, the grass drying process available in the Ecoinvent database could have led to an overestimation. In the cultivation phase, plastics production is the most energy-intensive process.	solar drying of *Laminaria digitata* solar heat for fermentation solar electricity for processing
Bioethanol production from *Ulva* sp. with different cultivation types [36].	bioethanol	50% of the environmental impacts originate from **seaweed production**. **Ethanol production** (saccharification and fermentation) contributes 26% to the environmental burden.	Infrastructure and equipment, nutrients, and electricity consumption for seaweed production account for a major part of impacts. Enzyme production has also large impacts on several impact categories.	solar thermal systems for preheating (fermentation, distillation) [46] solar electricity (membrane separation, sieve adsorption, freeze separation, extraction) thermal integration of thermal streams

Table 1. *Cont.*

Path	Main Product	Critical Process	Description	Potential Greening Solutions
Co-digestion of *Ulva lactuca* with agricultural waste for biogas production [42].	biogas, heat and electricity, compost	**Gathering** and **storage** of poultry manure constitute a system's hotspot. Moreover, **transport** and **biogas upgrading** allocate 31% of the total negative impacts.	Weekly transportation represents a notable impact in terms of fossil fuel consumption and climate change. Pressure Swing Adsorption (PSA) upgrading unit) consumes 29% of the total electricity.	solar drying solar heat for process solar electricity for pressing green fuels (biofuels, e-fuels)
Seaweed-based biostimulant production from onshore cultivated *Kappaphycus alvarezii* [56].	biostimulant	**Processing**, **bottling**, and **transport** to the processing center.	In the processing module, plastic packaging (HDPE production and blow molding process), electricity and shed accounted for 97.3% of the overall climate change impacts. Plastic packaging represented 54.2% of these impacts, while electricity accounted for 25.2%. Impacts of transporting sap by road found to be higher than those coming from rail or sea transportation.	solar electricity for process green fuels (biofuels, e-fuels) bioplastics reused and recycled plastics
Saccharina latissima pilot scale biorefinery for seaweed-based packaging bioplastic production [57].	bioplastic (film packaging)	Film fabrication	The highest impact in all cases derives from film fabrication, due to glycerol production. The use of glycerol in film compounding is the main hotspot.	solar heat for film fabrication solar electricity for processing green fuels (biofuels, e-fuels) bioplastics reused and recycled plastics
Saccharina latissima pilot scale biorefinery for seaweed-based packaging bioplastic production [58].	biologically active fucoxanthin, mannitol, fucoidans and alginates	Drying and $scCO_2$ extraction	Drying and electricity required for CO_2 pressuring during $scCO_2$ extraction are energy hotspots and contribute the most to environmental impacts.	solar heat for preheating solar electricity for pressure solar drying for seaweed

(iii) Nutrition products

Pathway (a) of Figure 4 presents the processes described by Zhang and Thomsen [49] to simulate a novel conceptual biorefinery of brown macroalgae aiming at high-value biomolecules extraction. Examined macroalgae are Laminaria digitata, Fucus vesiculosus, and Saccharina latissima. The main products of the proposed biorefinery system are fucoidan, laminarin, and feed supplements. Feedstock enters a reaction tank to be mixed with cold water and then heated up to a certain temperature. Solid-liquid separation (SLS) is achieved using a decanter centrifuge. The liquid stream undergoes consecutively high and low molecular weight cut-off (MWCO) ultrafiltration. Retained large molecules from high MWCO ultrafiltration, along with the solid fraction of the SLS are directed to a tank for acid extraction, and the output undergoes separation in a decanter centrifuge. The separated solid fraction is sent to a pasteurization unit. The permeate stream of low MWCO ultrafiltration is filtered in RO membranes before entering the pasteurization unit along with the aforementioned stream. Spray drying is the last process to extract the dry product in powder form. Parsons et al. evaluated the environmental sustainability of single-cell oils (SCOs) extraction from brown macroalgae Saccharina latissima, considering two fermentation alternatives: CSTR and low-cost raceway pond fermentation [52]. The main stages of the process demonstrated in path (b) are: (i) milling of cultivated seaweed, (ii) acid pretreatment and enzymatic hydrolysis to release the sugar content, (iii) CSTR or raceway pond fermentation, (iv) wet extraction of lipids using hexane, and v) refining of lipid product, i.e., neutralization, bleaching and deodorization. Path (c) in Figure 4 and path (e) in Figure 2 refer to the same process, with the first one highlighting the route of fish feed protein production [38]. Pathway (d) depicts the protein production pathway of *S. latissima* and *L. digitata* biorefinery, as described by Seghetta et al. [41]. As mentioned earlier, they included in their LCA study two storage alternatives: partial drying or chopping and ensilage. In both cases, the seaweed biomass goes through chopping, hydrolysis of sugars, microalgae growth, and dewatering to get a fish feed high in protein, as shown in Figure 4. In path (e) Nilsson and Martin [47] examined the onshore cultivation of red macroalgae Asparagopsis taxiformis for feed supplement production under the scope of LCA. This seaweed is known for its potential to mitigate the enteric methane emissions of ruminants up to 90% if used as a feed ingredient [59]. The described system consists of four main units: (i) Filtration with glass filter media and UV treatment (ii) Inoculum tank, in which water temperature and salinity are set at a favourable level, (iii) Reactor tanks for biomass production, integrating aeration, nutrient and CO_2 enrichment, and artificial illumination with LED fixtures, (iv) Drying, using refractance window technology (RWTM) [60]. Path (f) of Figure 4 is another viewpoint of the path described earlier as path (b) in Figure 2, demonstrating the route for animal-based protein extraction from green macroalgae *Ulva* sp. dual input biorefinery [37]. LCAs highlighted positive effects on climate change and marine eutrophication, while further optimization is needed in drying processes.

Alternative routes for nutrition products derived from macroalgae, often incorporate the drying process as the final step, particularly when it comes to protein-rich feed ingredients. In path (a) a gate-to-gate system boundary is employed, with a fictional unit of 1 kg dry biomass to examine three brown macroalgae species. This functional unit appears to be the most common among the examined LCAs. Path (b) focuses on offshore-cultivated *S. latissima* with a functional unit of 1 ton of refined product. Pathways (c) and (d), as described earlier, both use 1 ha of cultivated sea area as a functional unit. Pathway (e) presents a gate-to-gate approach for onshore-cultivated red macroalgae, defining the functional unit as 1 kg of dry seaweed. As described earlier, path (f) uses a cradle-to-grave attributional LCA for offshore *Ulva* sp. and sets as functional unit 1 ton of dry seaweed. Except for Parsons et al. who used the Brightway software for path (b), the other LCAs conducted using the SimaPro software.

Tables 2–4 summarize in SWOT format some key findings from the pathways analysed in Figures 2–4. For each of the three macroalgae products examined, a tailored SWOT analysis has been implemented based on the reviewed literature.

Table 2. SWOT analysis for macroalgae as a sustainable feedstock for bioethanol production [31,36–38].

Strengths	**Weaknesses**
• Macroalgae yield more biomass per unit area than terrestrial crops • The lack of lignin and cellulose simplifies biomass pretreatment processes like hydrolysis. • At a lab scale, various seaweed types have shown potential for ethanol fermentation, due to their carbohydrate content.	• Unlike microalgae, macroalgae biofuel production is in its early stages and many studies focus on hypothetical/pilot-scale applications. • Limited data tailored to bioethanol production from macroalgae in the Ecoinvent database cause uncertainties in LCA reports. • Energy-intensive enzyme production processes • Significant impact of water removal process on the total consumption. Potential overestimation may occur, as the process is based on grass drying.
Opportunities	**Threats**
• Integrating macroalgae culture into a fish farm (or offshore wind) could reduce the environmental impacts of nutrients needed for seaweed production (industrial symbiosis). • Avoiding carbon emissions associated with corn and molasse ethanol. • The substitution of fossil fuels with liquid biofuels adds to the environmental savings. • Cultivation of seaweed can improve marine environments by removing CO_2, heavy metals, pollutants and nutrients. • Macroalgae farming enhances rural economies, as seen in Indonesia and China.	• Risk of coastal area overexploitation • Local nutrient depletion should not be confused with remediation. • Competition with other existing coastal activities

Table 3. SWOT analysis for macroalgae as sustainable feedstock for energy production [31,41–45].

Strengths	**Weaknesses**
• Seaweed anaerobic digestion has been investigated as a promising energy conversion pathway. • High sugar content makes macroalgae suitable for biogas production. • Algal biomass contains useful microelements for the growth of anaerobic microorganisms (cobalt, iron, nickel). • Substituting conventional energy crops, macroalgae solves the conflict between bioenergy and food production. • Methane production could be a self-sufficient process, if the energy demand is covered by the produced heat and electricity.	• Current design is based on results from experiments and literature data. • Some input data from Ecoinvent are not tailored to seaweed. Energy production from seaweed is still at an early stage. • High sulphate concentration, heavy metals, salts and phenols after inappropriate pretreatment can inhibit methanogenesis. • Technological difficulties, complex harvesting, troubles in storage and the high cost of dehydration lower the interest in algal biomass for biogas production. • The most considerable impacts come from digestate handling, storage and field applications.
Opportunities	**Threats**
• Macroalgae cultivation avoids land use competition and deforestation issues. • Digestate can be used as soil fertiliser replacing the mineral ones. • Avoided emissions related to conventional methods add to the positive impact. • Co-digestion of seaweed with agricultural waste could present a useful solution. • Collecting excess algae biomass can reduce coastal pollution, serving at the same time as substrate in biogas plants. • Co-digestion with other substrates, like chicken manure, can lower the sulphate concentration and achieve a good C:N ratio.	• Risk of coastal area overexploitation. • LCA should include the management of digestate and its distribution to the farmers to be re-used as fertiliser • Competition with other existing coastal activities

Table 4. SWOT analysis for macroalgae as a sustainable feedstock for nutrition products [37,38,41,47,49,52].

Strengths	**Weaknesses**
• Protein-rich fish feed ingredients serve as substitute to plant-based (soy) and animal- based proteins • Sugar content of seaweed makes them ideal feedstock for high-value chemicals • Wide range of food applications	• Simplifications and assumptions in process modelling and add uncertainties LCA results. A significant portion of data relies on pilot tests and lab experiments. • The yield of proteins declines above certain temperatures. • Insufficient information for different amino acids in seaweed proteins. • Materials of the infrastructure used in cultivation and energy consumption for dewatering can add significant burdens to the overall environmental performance, overshadowing the positive effect of protein substitution. • Challenges regarding production upscaling.
Opportunities	**Threats**
• Significant positive economic impact from protein production • Seaweed is an attractive alternative source in the protein market, as a substitute for animal-based protein. • Seaweed protein can be marketed as an optimal ingredient for fish feed, given the increased demand and the raise in protein prices. • Addressing the issue of feed shortage • Including certain macroalgae in ruminants' feed composition is a promising way to reduce methane emissions.	• Final product must comply with the concentration thresholds of undesirable substances (heavy metals) set by regulation. • Protein production from seaweed is still in developing stage • Emerging technologies for seaweed utilization in the context of biorefineries are difficult to assess • Environmental challenges regarding ocean farming • Profitability is susceptible to price fluctuations

LCA Findings

Regarding system boundaries assessed, cradle-to-grave was the most utilised boundary (43%), followed by cradle-to-gate (38%). Only 3 studies considered gate-to-gate boundaries, while just one assessed the life cycle from a cradle-to-cradle perspective. As for the LCI modelling perspective, the majority of LCA studies (52%) did not mention the LCI modelling perspective, though they implicitly used an attributional approach. The rest of the studies explicitly stated that they used either an attributional (19%) or a consequential (29%) approach. Concerning functional units, all reviewed studies considered an output-related functional unit, with the majority focusing on the product (71%). Others considered energy (14%), the cultivated area (9%), and a Basket-of-Products (9%). For tools used in conducting the LCA, SimaPro was the most commonly used (67%), followed by GaBi (14%). Brightway2 was used in 9% of the studies, while some (14%) did not mention using a specific tool. Regarding LCIA methods, ReCiPe was the most utilized (67%). Other methods used included CML (19%), EF (9%), ILCD (9%), CED (9%), USEtox (9%), and Eco-indicator 99 (5%). The most frequently assessed impact categories were climate change (CC) (95%), eutrophication (E) (86%), acidification (A) (71%), resource depletion (RD) (76%), human toxicity (HT) (67%), ecotoxicity (Etox) (57%), and water use (WU) (52%). Regarding seaweed species examined in these studies, *Saccharina* sp. was the most frequently used (33%), followed by *Laminaria* sp. (29%) and *Ulva* sp. (19%). Other studies used species of *Chlorella* sp. (10%), *Octhoedes* sp. (5%), *Gracilaria* sp. (5%), *Kappaphycus* sp. (5%), *Asparagopsis* sp. (5%), while 2 studies did not specify the species utilised. From the pathways studied, 19% of the facilities were based in Denmark, 4.8% in France, 9.5% in Ireland, 9.5% in Norway and 4.8% in Sweden, utilising Northern seaweed species. Among the studies, 9.5% were based in India, 4.8% in Israel and 4.8% in South Africa, which utilised a native seaweed species in its area.

Table 5 provides a quantitative summary of the most frequent impact categories reviewed in this study. There were some limitations regarding the analysis, as some studies did not provide numerical results but rather a contribution analysis; therefore, they are not included in this table. Another difficulty encountered was the use of different

LCIA methods across studies, which resulted in reporting results in different units and using different FUs. Each impact category is reported based on each study's functional unit. Most studies reported at least on Climate Change, and some also focused on the sequestration of nitrates during cultivation, which resulted in a negative net impact for marine eutrophication.

A large variability among the results is observed, because there are differences among methodological aspects, including FUs, system boundaries, and types and quality of data assessed. Additionally, each study was analyzed for various technological readiness levels, while other studies conducted a scenario analysis comparing the base system to a novel optimised one. For instance, in [49], the authors compared a pilot facility with an industrial facility, highlighting a significant difference in impact categories between the two, with the industrial-scale system performing better. Additionally, the results were influenced by the cultivation technique utilised in each study. For example, in [52], a system utilising CSTR or a raceway pond was assessed.

The main challenge within these systems was electricity consumption, which recurred as a hotspot in multiple studies, especially for processes such as seaweed drying, cultivation, and other biorefinery processes. Seaweed drying was frequently highlighted as a significant burden across various life cycles. Regarding cultivation techniques, specific methods such as offshore farming and raceway ponds influenced environmental impacts, with some techniques causing human and ecosystem toxicity problems or requiring high energy inputs. Toxicity problems arose from the use of materials such as nylon ropes in cultivation systems, suggesting that natural alternatives could mitigate these impacts [38]. Another major hotspot was transportation and offshore farm maintenance, due to the use of fossil fuels, influencing the life cycle. Additionally, ref. [45] highlighted the critical role of biomass composition (such as dry solid content, salt, etc.) in impacting various categories. Seaweed often performed better in certain categories like marine eutrophication compared to other feedstocks (e.g., energy crops) in systems producing biogas. In two cases [36,56], the bioextractive capacity of macroalgae biomass to sequester carbon and nutrients (i.e., nitrates) is mentioned, providing additional climate and marine eutrophication mitigation benefits.

Table 5. Summary of the results of the LCIA of the reviewed pathways.

Ref.	FU	Impact Categories							Notes
		CC (kg CO_2, eq.)	ME ((kg N, eq.)	A ((kg SO_2, eq.)	RD ((kg Sb, eq.)	HT ((kg 1,4-DB, eq.)	Etox ((kg 1,4-DB, eq.)	WU ((m^3))	
[31]	1 t of dry seaweed	106~398	x	1.11~6.63	-7.8×10^{-4}~-6.5×10^{-3}	1.43×10^{2}~4.42×10^{2}	-1.37×10^{5}~3.43×10^{5}		
[38]	1 ha sea under cultivation	$[-2.8\sim6.6] \times 10^{2}$	−84.6~−11.0			* $[16.5\sim31.5] \times 10^{-4}$			* CTUh units
[41]	1 ha offshore cultivation	$[-18.7\sim-2.6] \times 10^{2}$	−43.6~−13.6			* $[22.8\sim46.5] \times 10^{-4}$			* CTUh units
[43]	1 MJ biogas 1 t feedstock	13.9 160.9		[a]0.2 0.9					
[44]	1 t dry *S. Latissima* 1 kg sodium alginate	921 2.73							
[45]	1 MJ of biomethane	2.6~5.1	[−2.2~0.03]	$[1.15\sim3] \times 10^{-4}$					
[49]	1 kg dry seaweed	[18.6~47.9] [3.8~11]						[0.7–1.8] [0.1~0.2]	Pilot, Industrial-scale
[52]	1 t refined SCO	[5663] [6188]	[−3] [−2]	[49] [51]		[3826] [4270]	[95] [116]	[−134] [−101]	CSTR, Raceway
[48]	1 t dry *E. maxima*	[5187.6] [25,665.4] [13,530.3]	[1.8] [3.6] [1.8]					[703] [529] [197.3]	scenario 1 scenario 2 scenario 3
[50]	1 kL Gracilaria extract	73.1	0.1	0.3		9.2	0.8	153	
[51]	1 kg of Lactic acid	11	1.1×10^{-3}	5×10^{-2}		7.4	29.7	0.46	
[53]	1 kg of Lactic acid	[530] [90]	[0.09] [0.02]						Base Optimized system
[54]	0.7 g of essential terpene oils	61.24	x	0.26	0.42	36.5	31.6		
[55]	1 t dry seaweed		[−32.3] [3.1] [−29.2]						Paths: Fertilizer Landfill Incineration
[56]	1 kL Gracilaria Extract	118.6	0.2	0.5		30.3	1.5	262	
[57]	1 kg of bioplastic film	[2.3~3.7]	$[-2.7\sim-1.5] \times 10^{-4}$	$[-8.8\sim-5.6] \times 10^{-3}$		[−42.3~8.2]	[102~309.7]	$[1.4\sim3.6] \times 10^{-2}$	
[58]	6 g of extract	[1.6~14.3]							

4. Discussion and Conclusion

4.1. SWOT Analysis

The implementation of SWOT analysis can shed light on the vague aspects of emerging scientific research, not only serving as a tool to review the current state of the examined technological sector, but also as a guide that highlights the challenging paths that need to be explored and improved by stakeholders to achieve sustainable development. SWOT analysis is a useful tool to identify the internal Strengths and Weaknesses and also understand the external Opportunities and Threats of the examined system. The extensive field of macroalgae applications should be examined and evaluated as a whole, regarding its prospects and limitations. In this way can be formed the bigger picture about the feasibility of the larger scale macroalgae exploitation by the industry. Table 6 presents a detailed overview of the assets and bottlenecks of macroalgae utilization as a sustainable biorefinery feedstock, including facts and common conclusions extensively analyzed in the available bibliography. This SWOT aims to demonstrate the inherent strengths of macroalgae as a renewable source of various value-added products; to assess the current weaknesses of this untapped feedstock; to present the driving forces for this sector to become more competitive, and to expose the potential external threats that should be considered within a responsible and sustainable exploitation plan.

Table 6. Overall SWOT summary of macroalgae as sustainable and profitable biorefinery input.

Strengths	**Weaknesses**
• A biological source, very often available and unexploited. • Capacity to produce multiple value-added biorefinery products at the same time, serving many industry sectors. • Well-known food ingredient, safe for food applications. • No terrestrial land, freshwater, or fertilizer needed for cultivation. • Certain species thrive despite facing harsh climate conditions. • Higher growth rates/yield than terrestrial crops. • Low lignin content, so lower energy demand for processing. • Potential CO_2 sequestration technology. • High carbohydrate content, favourable for biofuel production. • Capability for onshore or offshore cultivation. • A Small portion of the full macroalgae potential is yet revealed. There is a fast-growing research interest.	• High collection work required. • Algae needs a considerable amount of water and CO_2 to grow. • Unsteady supply of biomass throughout the year (seasonality). • Great energy demands during processes due to high water content (post-harvesting phase). • Limited knowledge of different species' properties, suitability and resilience to adverse factors, like climate change. • Lack of accurate data, uncertainties in LCA reports. • Comprehensive knowledge of biomass composition is required to achieve efficiency. • Algal biorefinery concept is a low TRL technology. • Scalability/Knowledge gaps about scale-up requirements. • Significant investment and operation costs. • At present, more CO_2 is produced by processing than the amount captured in the cultivation phase. • Low content of lipids, production of biodiesel from seaweed is not efficient. • Conversion of macroalgae to biofuel requires energy-intensive processes. • Future bioproducts may not be compatible with current infrastructure. • Bio-accumulated substances may be found in the feedstock biomass.
Opportunities	**Threats**
• The European and national green policy (to meet the global policy goals). • The current trend of bioproducts. • Several cofinancing opportunities. • Uncovered global demand for energy and food. • Helping the untapped sector of the Blue Circular Bioeconomy. • Reducing macroalgal bloom issues while producing valuable products. • Reducing emissions from the agriculture industry (macroalgae as feed and fertilizer). • Avoiding carbon emissions associated with corn ethanol. • Macroalgae absorb CO_2 during cultivation and supply the aquatic environment with oxygen. • Algae have the potential to remove pollutants and prevent eutrophication in coastal areas. • New job opportunities and economic growth for local communities. • Facing the problem of plastic pollution. producing algae-based biodegradable products. • Market development.	• High cost versus already industrialized methods. • Knowledge gap on how to sustainable expand seaweed aquaculture. • Risk of coastal area overexploitation causing environmental degradation. • Unexplored environmental burdens from cross-coastal cultivation, harvesting and transportation. • Unmapped available areas for seaweed cultivation. • Labour and material costs differ among countries. • Uncertain demand for seaweed outside Asia. • Need for skilled workers. • Labour for harvesting and post-harvesting phase have to follow seasonal variations. • Geographical availability may lead to increased transport requirements. • Effects of climate change (high water temperatures and adverse weather conditions) on algae global distribution. • Conflicts over the area use. • Invasive species could harm the local ecosystems. • Constraints regarding regulation, licensing and maritime spatial plans. • Potential social scepticism on large-scale macroalgae biorefinery.

4.2. LCA Method Weaknesses

LCAs employed in previous studies exhibit various weaknesses that necessitate consideration. Addressing these weaknesses is vital for enhancing the robustness and reliability of LCA studies, ensuring that the assessments accurately reflect the environmental hotspots of the processes in biorefineries. Forming an LCI requires the collection of high-accuracy data, crucial for ensuring a reliable LCA. LCIs based on literature and lab-scale data, due

to a lack of industrial and large-scale industry data, pose limitations on the comprehensiveness of the findings. Upscaling experimental performance data from lab-scale systems introduces numerous complicated factors affecting the scale-up performance of large-scale systems. Reliance on such data could lead to high uncertainty related to environmental aspects of the study [52]. Additionally, the LCA of immature and novel biorefinery systems introduce uncertainties due to their nature and their low TRL [48]. The majority of the available macroalgae LCA research relies on hypothetical biorefinery facilities with the use of extrapolated data from lab-scale units [32]. Substituting critical processes of seaweed drying, e.g., substitution of drying of seaweed with grass drying or milk spray drying, could add more uncertainties to the results [61]. Another potential issue is the replacement of macroalgae bioethanol refinery data with bioethanol production from other types of biomasses, such as bioethanol production from potatoes, rye, and corn [62]. Moreover, material flows of macroalgae in biorefinery processes should also be considered, in case they are substituted with assumptions about the literature data.

4.3. Examined Pathways

The five pathways illustrated in Figure 1 for bioethanol production highlight the processes of hydrolysis, fermentation, and distillation as core steps for ethanol recovery. Common pretreatment of wet seaweed is partial drying—to facilitate their transport from the cultivation site—and chopping. Apart from the usual hydrolysis and fermentation process, it is possible to recover ethanol and a mix of heavier alcohols from VFA content, by implementing partial anaerobic digestion and hydrogenation. An alternative way, as described above, is the fermentation of the liquid content separated from the hydrothermal reactor's output. Solid by-products can be utilized as fertilizers, feed ingredients and hydrochar. Results of these studies indicated that bioethanol production from seaweed is an environmentally efficient biofuel in contrast with gasoline.

Six pathways implemented to produce biogas through anaerobic digestion were analyzed. Biogas is utilized by CHP systems that provide on-site electricity through steam turbogenerators. Part of the steam in the final stage of steam generators can be retrieved to heat anaerobic digester feed streams. However, in the case of [42], residues that remain after the extraction of alginate and the production of film are used to achieve a zero-waste concept. Results from these studies indicated that sustainable energy production is achievable from macroalgae. In almost all scenarios, there were environmental benefits in terms of mitigation of climate change and marine eutrophication (nitrogen and phosphorus are extracted during the cultivation phase of seaweeds) [37]. Even so, there are some issues to be addressed concerning the optimization of seaweed pre-treatment processes and harvesting procedures and reducing toxicity arising from high levels of phenols, heavy metals, salts, sulphides and volatile acid compounds, which can impede methanogenesis [41].

Human and animal nutrition products are among the most popular products derived from macroalgae. A typical system employs techniques like chopping, dewatering, and drying and processes such as fermentation, pasteurization, and hydrothermal methods. Depending on the macroalgal species, sometimes acid pretreatment is required prior to enzymatic hydrolysis to breakdown the crystalline structure of cellulose. Feed supplements end up as by-products after separation processes of liquid and solid streams. Figure 3 outlined six pathways that result in high-value protein supplements. These ingredients could be produced as the primary or as co-product of other valorization pathways e.g., bioethanol and biomethane production. However, a potential issue could arise from the bioaccumulation of heavy metals to fishes due to the heavy metal contents of these supplements. Findings revealed that seaweed biorefineries have the capability to enhance the growth of the blue economy and present a promising economic opportunity within the higher-value oils market. LCAs studies indicated climate change and marine eutrophication as impact categories that benefit from these production chains. Optimization of drying processes is necessary to reduce environmental impact.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/chemengineering8040074/s1, Table S1: The potential of macroalgae biomass valorization on the UN Sustainable Development Goals implementation, Figure S1: Data for EU retrieved from Statista platform; Figure S2: Data for the US seaweed market, retrieved from Statista platform.

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