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Life cycle assessment of seaweed-based biorefineries: environmental impacts, hotspots, and pathways for a circular bioeconomy

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Seaweed-based biorefineries are increasingly recognized as promising contributors to the circular bioeconomy, offering renewable pathways for fuels, materials, fertilizers, cosmetics, and bioactive compounds. This review synthesizes approximately sixty life cycle assessments (LCA) studies covering diverse product categories, including biofuels, bioplastics, fertilizers and biostimulants, cosmetics, protein and feed, construction materials, food additives, and biochemicals. Across these applications, drying and energy-intensive extraction/crosslinking processes consistently emerge as dominant hotspots, often accounting for 50–70% of total GWP. Consequently, analysis shows that substituting greener solvents (reducing GWP by 20–40%) and implementing renewably powered drying (reducing GWP by ∼15–25%) are the most critical levers for impact reduction. Fertilizers and biostimulants show potential to reduce greenhouse gas emissions through substitution of synthetic inputs, while bioplastics and biofuels highlight trade-offs between energy use and co-product valorization. Cosmetics, food additives, and construction uses remain underexplored but demonstrate niche opportunities for high-value and low-carbon products. Cross-cutting analysis reveals methodological gaps, including inconsistent functional units, narrow impact category coverage, and limited integration of techno-economic analysis. Cultivation-focused LCAs further underscore the influence of farming practices, seasonality, and feedstock quality on downstream performance. Key challenges include high moisture content, ash and salt constraints in thermochemical conversion, insecure feedstock supply, and fragmented system modeling. Addressing these requires harmonized LCA methodologies, improved pretreatment strategies, and integration of techno-economic analysis to bridge environmental and economic performance. Compared to previous reviews, this study advances the field by synthesizing product-specific LCAs alongside cultivation studies, highlighting underrepresented products such as biostimulants and construction materials, and framing hotspots at process, system, and policy levels. Seaweed biorefineries present significant opportunities for climate mitigation, resource efficiency, and sustainable industry development, provided that future assessments expand in scale, scope, and methodological rigor.

Sustainability spotlight

This comprehensive review synthesizes the life cycle environmental impacts of seaweed-based bioproducts, which are poised to become a cornerstone of the circular bioeconomy. By identifying persistent hotspots (*e.g.*, thermal drying, solvent-based extraction) and proven mitigation levers (*e.g.*, renewable energy integration, green solvents), this work provides an actionable roadmap for researchers and industry. The findings directly support the advancement of several UN Sustainable Development Goals, including SDG 9 (Industry, Innovation, and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action), by guiding the development of viable, low-carbon, and resource-efficient alternatives to fossil-based products.

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1. Introduction

Modern society faces escalating challenges from climate change, resource depletion, food insecurity, and the growing demand for sustainable products.[1,2] The global population is projected to reach 9.7 billion by 2050, which places immense pressure on food, energy, and material supply chains.[3,4] To maintain global economic growth while minimizing environmental degradation, the utilization of renewable feedstocks and

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clean energy alternatives must be accelerated. This transition is essential for reducing dependency on fossil fuels, conserving natural resources, and enabling a shift toward a more sustainable bio-based economy.[5] An increasing number of countries are recognizing bioeconomy as a strategic pathway to sustainable development. For instance, the European Union has adopted a Bioeconomy Strategy,[6] while the U.S. has issued an Executive Order on Advancing Biotechnology and Biomanufacturing.[7] Similarly, countries like China, India, and Brazil are investing in bio-based innovation ecosystems and biomass valorization programs.[8] These efforts aim to meet several of the 17 Sustainable Development Goals (SDGs) set by the United Nations (UN), particularly those related to climate action (SDG 13), responsible consumption and production (SDG 12), and affordable and clean energy (SDG 7).[9,10] These efforts also follow some of the 12 principles of Green Chemistry, such as using renewable feedstocks (Principle 7), being energy efficient (Principle 6), designing for degradation (Principle 10), and using safer solvents and auxiliaries (Principle 5).[11]

Biorefineries, which convert biomass into marketable products such as biofuels, bioplastics, food ingredients, pharmaceuticals, and fertilizers, are central to this transition. They enable the eco-innovative and sustainable transformation of biological resources through integrated processes, many of which align with SDG targets for clean energy (SDG 7), economic growth (SDG 8,9,12), and climate mitigation (SDG 13).[10] For example, ethanol derived from agricultural residues or biodiesel from algae directly substitutes fossil-based fuels and reduces carbon emissions. Importantly, because biomass is of biogenic origin, carbon dioxide (CO_2) released during its conversion is considered part of the natural carbon cycle. Under current life cycle assessment (LCA) guidelines and IPCC recommendations, these biogenic emissions are accounted for separately and typically not modeled as contributing to a net increase in atmospheric CO_2 levels.[12] Biorefineries are categorized into three generations based on the type of feedstock used and the technological advancements involved. In order to develop sustainable and profitable bio-based industries, these generations must be recognized.[13] First-generation biorefineries rely on food crops such as corn, sugarcane, and wheat,[14] while these systems are commercially established and have well-developed supply chains, they pose concerns related to food-versus-fuel conflicts, land use change, and biodiversity loss. Second-generation biorefineries utilize non-food lignocellulosic biomass, including crop residues, forestry waste, and dedicated energy crops.[15] These offer improved environmental benefits by reducing competition with food systems and utilizing agricultural waste; however, they require more complex and energy-intensive pretreatment processes. Third-generation biorefineries are based on algal and microbial feedstocks, including microalgae and seaweed, which are fast-growing, high-yielding, and capable of growing in saline or wastewater environments.[16] Unlike earlier generations, these systems do not require arable land or freshwater, can perform nutrient bioextraction to mitigate coastal eutrophication, and provide circular residues for co-product valorization, significantly reducing the environmental footprint of biorefineries. Later generations are preferred not only because they reduce pressure on land and freshwater resources, but also because they align more closely with circular bioeconomy principles and global climate goals. The transition to third-generation biorefineries therefore represents a strategic evolution toward low-impact, high-efficiency, and carbon-neutral production systems, as depicted in Fig. 1.[13–16]

Seaweed-based biorefineries, often classified as third-generation systems, offer several unique advantages over first-generation (*e.g.*, corn, sugarcane), second-generation (*e.g.*, lignocellulosic biomass), and other third-generation options such as microalgae. Unlike 1 generation and 2nd feedstocks, seaweed cultivation requires no arable land, freshwater, or synthetic fertilizer inputs, significantly reducing competition with food systems and freshwater stress (SDG 2 & 6).[8] In comparison with microalgae, seaweed cultivation is often lower in energy demand due to its passive nutrient uptake from seawater and ease of harvesting without expensive photobioreactors or closed systems. From an environmental perspective, several LCA studies suggest that seaweed cultivation offers lower Global Warming Potential (GWP) and eutrophication impacts per kg of biomass compared to first-generation (*e.g.*, corn, sugarcane), second-generation (*e.g.*, lignocellulosic biomass), and other third-generation options such as microalgae, particularly when integrated into near-shore or offshore farming systems with minimal land, fertilizer, and freshwater inputs. However, challenges persist. Seaweed exhibits high moisture content (80–90%), necessitating energy-intensive drying or dewatering unless co-located with processing units.[18] To provide a more intuitive comparison of GWP-related drivers across biorefinery generations, a qualitative "traffic-light" matrix is presented in Fig. 2, summarizing key conditions such as land use, fertilizer demand, drying intensity, offshore logistics, and renewable heat integration.

Additionally, the geographic constraints, favoring temperate or tropical coastal zones, may limit year-round cultivation and scalability in inland or landlocked regions. Cost-wise, seaweed cultivation remains labor- and infrastructure-intensive, especially where mechanization or offshore logistics are not well-developed. While microalgae may yield higher-value compounds (*e.g.*, lipids, pigments), their cultivation costs and energy footprints are generally higher. In contrast, seaweed biorefineries can enable cascaded extraction (*e.g.*, protein, biostimulants, and polysaccharides) that promotes circularity and whole-biomass utilization. Thus, seaweed-based biorefineries strike a balance between ecological sustainability and process feasibility, positioning them as a promising feedstock for blue bioeconomy development in suitable coastal geographies. Seaweed species, in particular, are fast-growing, with cultivation cycles typically ranging from 3 to 8 months and achieving annual productivities of 1–5 tonnes of dry weight per hectare.[19] This high-yield, rapid rotation potential makes them attractive feedstocks capable of growing in saline or wastewater environments. When evaluating their role in biogenic carbon sequestration, this short rotation period must be accounted for using dynamic assessment methods (*e.g.*, dynamic LCA, GWPbio) that consider the temporal balance between carbon uptake and

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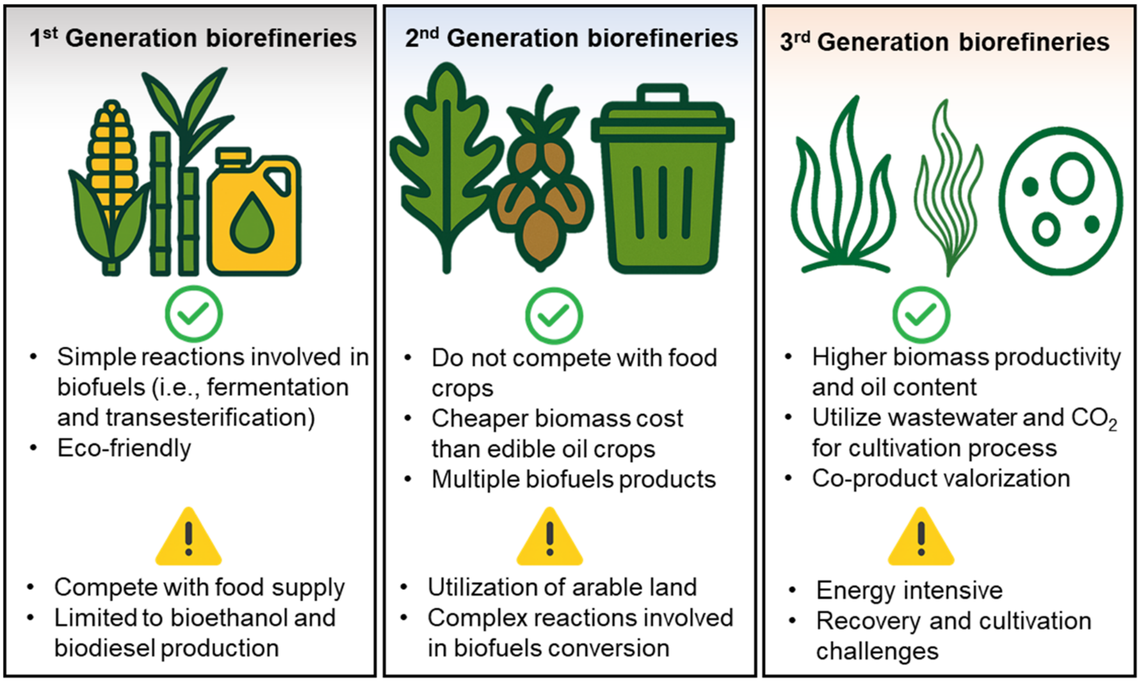

Fig. 1 Classification of seaweed-based biorefinery systems based on biorefinery generations, illustrating technological evolution from traditional use (first generation) to advanced cascading extraction and integration with bioenergy and co-products (third generation).[17]

release, and the ultimate fate of the carbon in end-use products or sequestration pathways.[20,21]

Macroalgae, commonly referred to as seaweeds, possess significant potential to completely or partially replace terrestrial biomass and generate sustainable bioenergy and biomaterials.[22] This is because the cultivation of seaweed does not require either land or freshwater.[23] Furthermore, seaweed has the potential to provide a vast range of sustainable products that include food, cosmetics, biodiesel, biofuel, biogas, bioplastics, pharmaceutical, fertilizers, and other chemicals.[1,24] Moreover, seaweed cultivation directly decarbonizes multiple sectors by absorbing CO_2 and provides co-benefits such as protecting marine biodiversity, reducing eutrophication, and conserving land and freshwater resources.[25,26]

Previous reviews on seaweed biorefineries have primarily focused on technological pathways, conversion processes, or economic feasibility, often treating environmental performance only briefly or in isolation.[24,27,28] In contrast, this review provides the systematic synthesis of life cycle assessment (LCA) studies across eight major product categories, biofuels, bioplastics, fertilizers and biostimulants, cosmetics, protein and feed, construction materials, food additives, and biochemicals. Unlike earlier reviews, it explicitly integrates cultivation-focused LCAs to highlight the role of farming practices, seasonality, and feedstock quality in shaping downstream impacts. This paper also advances the literature by identifying cross-cutting environmental hotspots (*e.g.*, drying, transport, extraction, cross-linking, infrastructure) and linking them with methodological challenges such as inconsistent functional units, limited Techno-Economic Analysis (TEA)-LCA integration, and under-representation of impact categories. Moreover, the review emphasizes underexplored product streams, such as biostimulants, cosmetics, and construction applications, thereby expanding the scope beyond conventional biofuels and

Driver / Generation	1st Gen (Corn/Sugarcane)	2nd Gen (Lignocellulosic)	3rd Gen (Microalgae)	3rd Gen (Seaweed)
Land Use / Land-Use Change	High	Medium	N/A	N/A
Fertilizer Demand	High	High	Low	Low
Drying Intensity	Low	Medium	High	High
Offshore Logistics	N/A	N/A	Medium	High
Renewable Heat Integration	Medium	High	Medium	High

Fig. 2 Qualitative traffic-light matrix of GWP drivers across biorefinery generations. Color coding (red-high, yellow-medium, green-low) reflects the relative contribution of each process driver to the GWP of biorefineries based on literature synthesis. This matrix highlights the eco-efficiency advantages of seaweed-based systems and the context-dependent trade-offs associated with land use, fertilizer input, energy intensity, and logistics.

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bioplastics. Together, these novelties position the study to not only consolidate fragmented evidence but also to outline research priorities and opportunities for scaling seaweed biorefineries within the circular bioeconomy.

2. Materials and methods

2.1. Literature search strategy and selection of LCA studies

This study conducted a systematic literature review of LCA studies related to seaweed biorefineries. Two major academic databases were used: Scopus (https://www.scopus.com, accessed on 1 May 2025) and Web of Science (https://www.webofscience.com, accessed on or before 1 May 2025). The following search strings were employed:

• On Scopus: "LCA" OR "life cycle analysis" AND "environmental impact" AND "seaweed" (searched within title, abstract, and keywords).

• On Web of Science: "life cycle assessment" OR "LCA" AND "seaweed" AND "environmental impact" (topic search across all indexed fields).

After compiling records from both sources, duplicates were removed. The remaining entries underwent a two-stage screening process. First, titles and abstracts were reviewed for relevance. Then, full-text articles were assessed against a set of inclusion and exclusion criteria.

2.1.1. Inclusion criteria. • Studies explicitly applying process-based LCA, following ISO 14040/14044 or ILCD standards, and using real or modeled process inventory data.

• Studies that clearly apply and report LCA methodology with quantifiable environmental impacts.

• Focus on seaweed-derived bioproducts (*e.g.*, fuels, plastics, fertilizers, protein, cosmetics).

2.1.2. Exclusion criteria. • Studies relying solely on economic, social, or techno-economic analyses without LCA modeling.

• Reviews, commentaries, or conceptual works not including formal LCA methodology.

A total of 361 records were retrieved initially (Scopus = 205; Web of Science = 156). After screening and eligibility assessment, 60 studies were included in the final review.

2.2. Data extraction and thematic analysis of LCA studies

The studies were systematically reviewed to extract relevant methodological and contextual information. The data extraction focused on the following parameters:

• Study origin (country).

• Seaweed species and product type (*e.g.*, brown, red, green; bioplastic, biofuel, fertilizer, *etc.*)

• Functional unit (FU).

• System boundary (*e.g.*, cradle-to-gate, cradle-to-grave, cradle-to-cradle).

• Impact assessment method and impact categories.

• Identified environmental hotspots.

The extracted information is synthesized in Table 3, which provides an overview of key characteristics and findings across all reviewed LCA studies on seaweed-based biorefineries.

3. Overview of seaweed cultivation, harvesting, and biomass conversion technologies

This section reviews key aspects of macroalgal resources that are foundational to seaweed-based biorefineries. It begins with an overview of major seaweed types classified based on their pigmentation and biochemical profiles: red, brown, and green. This is followed by a summary of global cultivation trends and harvesting techniques. These elements are essential, as species-specific composition and farming practices strongly influence both environmental impacts and techno-economic performance in biorefinery pathways. The section concludes with an outline of key value-added products (*e.g.*, bioplastics, biofuels, biostimulants) derived from seaweed, highlighting their relevance to circular bioeconomy and sustainable development. Understanding this foundation is critical for linking upstream biomass characteristics with downstream processing, environmental assessment, and product development.

3.1. Overview of seaweed and type

Seaweed cultivation is rapidly emerging as a key component of sustainable aquaculture, offering ecological benefits such as

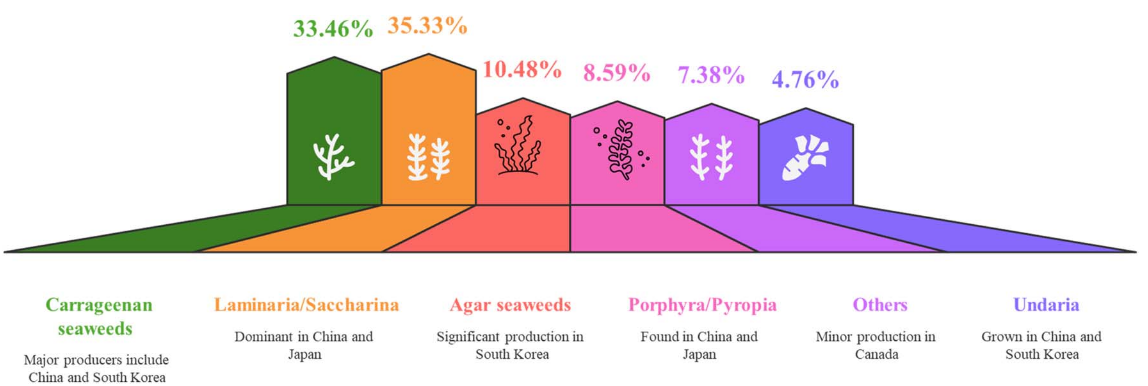

Fig. 3 Global seaweed production by major groups, showing *Laminaria*/*Saccharina* leading at 35.33%, carrageenan seaweeds at 33.46%, Agar seaweeds at 10.48%, *Porphyra*/*Pyropia* at 8.59%, other seaweeds at 7.38%, and *Undaria* at 4.76%; key production regions noted for each group (*e.g.*, China, South Korea, Japan, Canada).[94]

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biodiversity enhancement and habitat provision while supporting expanding production across Asia. Asian countries such as China, Indonesia, the Philippines, Japan, and South Korea lead global seaweed production due to favorable coastal environments and well-established farming infrastructure. From 2000 to 2020, global seaweed production increased significantly from 10.6 million tons to 35 million tons, driven by demand for hydrocolloids and sustainable materials. The most dominant cultivated species include *Undaria*, *Pyropia*, *Gracilaria*, *Eucheumatoids*, and *Saccharina*.[87] The cultivation of *Phaeophyceae* (brown algae) and *Rhodophyta* (red algae) has been increased by 3.1 million tons to 16.4 million tons, and 1 million tons to 18.3 million tons respectively. However, a significant decline has been observed in *Chlorophyta* seaweed (green algae).[88] Over 95% of global macroalgae production is dominated by a few key seaweed groups, including *Kappaphycus* and *Eucheuma* (33.5%), *Gracilaria* (10.5%), *Porphyra*/*Pyropia* (8.6%), *Undaria* (7.4%), and *Laminaria saccharina* (35.4%), refer Fig. 3. In contrast, Europe contributed only 287 033 tonnes of seaweed in 2019, representing just 0.8% of global production.[89] A World Bank analysis of 10 emerging seaweed markets estimates that the global commercial potential of the seaweed industry could reach USD 11.8 billion by 2030, driven by demand in bio-based materials, food additives, pharmaceuticals, and climate-focused applications.[90] Despite this forecast, much of the sector's economic value remains untapped due to limited processing capacity, policy support, and market access, especially in developing nations. Moreover, another World Bank report in 2016 projects that increasing seaweed cultivation by 14% annually could result in production of 500 million dry tons by 2050, potentially contributing to a 10% increase in global food supply. This expansion is also linked to improved income generation for coastal communities and enhanced quality of life, although these two latter benefits are more qualitative and context-dependent rather than direct 10% increases.[91] Macroalgal biomass contains various polysaccharides, primarily made up of glucose units known as glucans. The dominant glucans differ by algal type: in green algae, cellulose and starch are prevalent; in red algae, cellulose and floridean starch are common; while brown algae mainly feature cellulose and laminarin.[92,93]

Seaweeds are broadly classified into three main groups based on the pigments they use for photosynthesis: green (*Chlorophyta*), red (*Rhodophyta*), and brown (*Phaeophyta*).[95] These marine macroalgae typically consist of 80–90% water and, on a dry weight (DW) basis, contain approximately 50% carbohydrates, 1–3% lipids, and 7–38% minerals.[96] Their protein content is highly variable across species, ranging from 10% to as high as 47% DW, and is rich in essential amino acids.

Around 1500 recognized species of green macroalgae occur in shallow coastal environments such as bays, tidal pools, and estuaries. Prominent genera include *Ulva*, *Codium*, and *Halimeda*, which contain chlorophylls A and B as well as carotenoids, typical of the broader Chlorophyta group.[97] A characteristic feature of this division is the presence of the complex sulfated heteropolysaccharide ulvan in their cell walls.[98,99] In addition, *Chlorophyta* are rich in carbohydrates, with cellulose and hemicellulose representing 53–70% of their dry weight.[100] Ulvan displays a variety of biochemical and functional properties that make it attractive for pharmaceutical and agricultural uses. However, its weak gelling capacity currently limits large-scale commercial exploitation. Interestingly, ulvan solutions are pseudoplastic; they exhibit low viscosity that decreases further when shear rate increases.[101]

Nearly 4000 identified species of red macroalgae occur in both cold, deeper waters and in warmer, shallower seas, making them one of the most widely distributed groups of marine algae.[102] Most species typically inhabit submerged or subtidal environments, although only a limited number can endure desiccation or direct exposure (p). A considerable portion of these algae contain a high percentage of carbohydrates in their dry weight (53–76%), primarily in the form of polysaccharides such as agar, cellulose, and carrageenan. Under favorable conditions, members of *Rhodophyta* can reach lengths of about four feet.[103] Asexual propagation takes place through non-motile spores, whereas sexual reproduction involves the union of spermatia with carpogonia (female gametangia), resulting in heterogamous offspring. These gametes are well differentiated into non-motile male and female cells. Some species allow calcium carbonate deposition on their fronds, contributing to the growth of algal reefs in marine ecosystems. Economically, red algae hold great value: for example, *Gelidium* is a major source of agar, while Irish moss (*Chondrus crispus*) is widely utilized for carrageenan production.[104,105]

Around 1500 different species of brown macroalgae exist across genera such as *Fucus*, *Laminaria*, *Himanthalia*, *Undaria*, *Alaria*, and *Ascophyllum*, all of which belong to the *Phaeophyta* division.[106] They are generally distributed in cooler waters of shallow marine zones. Brown macroalgae exhibits a diverse metabolic structure, with carbohydrate content ranging between 34% and 76% of their dry mass.[102] The distinctive brown coloration arises from a dark pigment that masks chlorophyll. Nowadays, seaweeds are utilized in various sectors including the production of industrial phycocolloids, animal and human nutrition, and agriculture, particularly as biofertilizers. Despite their impressive nutritional and functional potential, the full dietary value of seaweeds remains underutilized, largely due to the complexity of their structural polysaccharides.[107]

3.2. Seaweed cultivation and harvesting

In the past, seaweed was mostly collected from wild or natural habitats, which often led to overharvesting and strain on marine ecosystems. To make seaweed use more sustainable, researchers and farmers began developing new farming techniques to domesticate native species. The success of large-scale seaweed farming has depended on several factors, like how well a species can regenerate, its physical structure, and how it responds to environmental conditions such as temperature, light, nutrients, and water movement.[108] The cultivation method used usually depends on the specific type of seaweed. Some genera like *Eucheuma*, *Kappaphycus*, *Chondrus*, and *Gracilaria* can be grown through simple vegetative propagation. Others, such as *Laminaria*, *Undaria*, *Porphyra*, and *Enteromorpha*, rely on spores and need a more complex, two- or multi-step farming process because

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Table 1 Seaweed cultivation methods and its advantages and disadvantages[29]

Cultivation method	Advantages	Disadvantages
Floating raft	Promotes favorable environmental conditions; low capital cost; minimal infrastructure; suitable for nutrient-rich waters; enables passive nutrient uptake	Sensitive to weather changes; higher ecological risks due to drifting; uneven biomass growth patterns
Tube net	Lower risk from weather; uniform growth; suitable for deep water with minimal infrastructure	Requires more seedlings; limited reusability; higher material input and setup time
Off-bottom monoline	Easy to manage during low tide; low-cost setup	High seedling loss; sensitive to wind, tides, and storms; hard to control epiphytes; difficult to remove in bad weather
PVC pipe raft	Lightweight and easy to handle; low labor demand; reusable materials	Not biodegradable; higher fossil-based plastic footprint; less durable in high wave energy regions
Cage systems	Variety of cage designs possible; good for epiphyte control; can withstand harsh weather	High implementation and maintenance costs; risk of biofouling
Multiple raft longline	Suitable for large-scale operations; cost-effective per unit biomass; lower energy input per kg yield	Potential ecological impact (*e.g.*, shading, growth of unwanted organisms); risk of loss in extreme weather
Spider web	High productivity in constrained areas; supports polyculture systems; increases space-use efficiency	Susceptible to epiphyte growth; weather-sensitive

they don't survive well when propagated vegetatively. Whether a species grows clonally or as individual units also affects how it's farmed.[29,109] Clonal genera like *Gracilaria* and *Kappaphycus*, which can grow from fragments, are often directly planted into farming systems. There are many ways to farm seaweed, ranging from controlled environments like tanks and ponds to open-water systems using longlines or rafts. For species like kelp, hatcheries or nurseries are often needed for early growth stages, which makes the process more industrial. While many cultivation techniques have been explored, the most successful ones tend to be those that are cost-effective and easier to manage.[110] Different farming methods, such as fixed off-bottom, raft, or net systems, are used around the world (Table 1). Each method has its pros and cons; for instance, approaches like the off-bottom method, single raft, and hanging longline are particularly effective in shallow water, but may not perform as well in deeper or more turbulent conditions.[87]

Seaweed harvesting methods fall into two main categories: manual and mechanical (Table 2). In manual harvesting workers hand-pick or cut seaweed fronds; it is energy-efficient and allows for selective removal of mature biomass, which helps maintain high quality for downstream processing. It also minimizes damage to the holdfast and surrounding ecosystem, supporting regrowth in the next cycle. However, manual harvesting is labor-intensive, time-consuming, and generally limited to small-scale operations or high-value products.[111]

Mechanical harvesting uses specialized cutters, conveyor systems, or sensor-guided boats to collect large volumes quickly. This approach is well-suited for industrial-scale farms targeting bulk commodities like bioplastics feedstock.[112] Mechanical cutters can strip entire lines of seaweed in a single pass, dramatically reducing labor costs and turnaround time. On the downside, mechanical methods often cause more breakage of seaweed tissue and greater disturbance to the seabed and non-target organisms. The higher energy input and risk of mixed-species or immature fronds entering the process stream can also impact overall product quality and extraction efficiency.[30] Balancing these trade-offs is key when choosing the right harvesting strategy for a given farm size, target product, and environmental setting.

Table 2 Comparison of mechanical and manual harvesting[30]

Criteria	Mechanical harvesting	Manual harvesting
Technologies/techniques	Mechanical cutters, automated harvesters with quality sensors	Hand-picking
Scalability	High; ideal for large-scale bioplastics feedstock	Low; best for niche or high-value bioplastics
Costs	High initial investment, low labor costs; suited for bulk production	Low initial cost, high ongoing labor; suitable for high-value bioplastics
Impact on quality and yield	Medium: potential damage could affect biopolymer yield and extraction quality	High; careful selection preserves quality
Energy consumption	High; necessary for large-scale operations	Low; minimal energy usage, labor intensive
Extraction efficiency	Medium: risk of contamination or damage during harvesting could lower efficiency	High; selective harvesting ensures high-quality inputs for extraction
Suitability for bioplastics production	Best for mass production where quantity is prioritized	Suitable for high-quality, high-value bioplastics

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3.3. Seaweed biomass conversion technologies

Utilizing seaweed biomass to produce a wide array of bio-based products is a key strategy in advancing sustainable marine biorefineries. This section explores the various thermochemical, biochemical, and physicochemical processes used to transform seaweed into biofuels, bioplastics, biostimulants, and high-value co-products. Key technologies include anaerobic digestion (AD), fermentation, hydrothermal liquefaction (HTL), and enzymatic extraction, each offering distinct pathways for valorizing different fractions of seaweed biomass, refer Fig. 4. The ongoing research and technological advancements in seaweed processing and product development are creating new opportunities for green technology and infrastructure investment.

3.3.1. Biochemical conversion: anaerobic digestion and fermentation. The biochemical conversion of seaweed into biofuels and chemicals involves two technologies (AD and fermentation) and three pathways: the Sugar Pathway (SP), Volatile Fatty Acids (VFA) Pathway, and Methane Pathway (MP), each utilizing distinct biological mechanisms and recovery processes. Several studies find seaweed as promising feedstocks for biogas production using AD,[113,114] because of their readily hydrolysable sugars (*e.g.*, alginate and laminaran) and low cellulose and lignin content.[115]

Bioethanol derived from algal biomass represents an environmentally sustainable and renewable route for biofuel generation.[116] The fermentation process can be conducted through two main approaches: Separate Hydrolysis and Fermentation (SHF) and Simultaneous Saccharification and Fermentation (SSF).[117] In the SHF method, hydrolysis and fermentation occur as two distinct, consecutive steps.[118] In both cases, the hydrolysable sugars in seaweed (*e.g.*, laminaran and alginate) enter the SP, where they are converted into simple sugars that serve as substrates for microbial fermentation. These sugars are then fermented into bioethanol, while some intermediates can also feed into the VFA pathway. Non-glucans such as agar, carrageenan, and alginate require additional hydrolysis, and efficient conversion of glucans and non-glucans into fermentable sugars is essential to achieve higher ethanol yields.[117–119] In the SP, enzymatic hydrolysis is used to break down seaweed polysaccharides like cellulose and laminaran into fermentable sugars, without the need for acid pretreatment due to the absence of lignin in *Laminaria japonica*. The hydrolysate is then fermented using engineered *Escherichia coli* to yield ethanol at 0.281 kg kg^{-1} of dry *Laminaria japonica* biomass, followed by multi-step distillation and membrane separation to achieve 99.5 wt% ethanol purity.[120,121] The SP offers relatively high ethanol yields but often requires genetically engineered strains and strict control of fermentation conditions, which may increase operational complexity.

The VFA pathway leverages partial AD to convert biomass into VFAs (yield: 0.35 kg per kg dry seaweed), with methanogenesis inhibited to maximize acid production. VFAs are

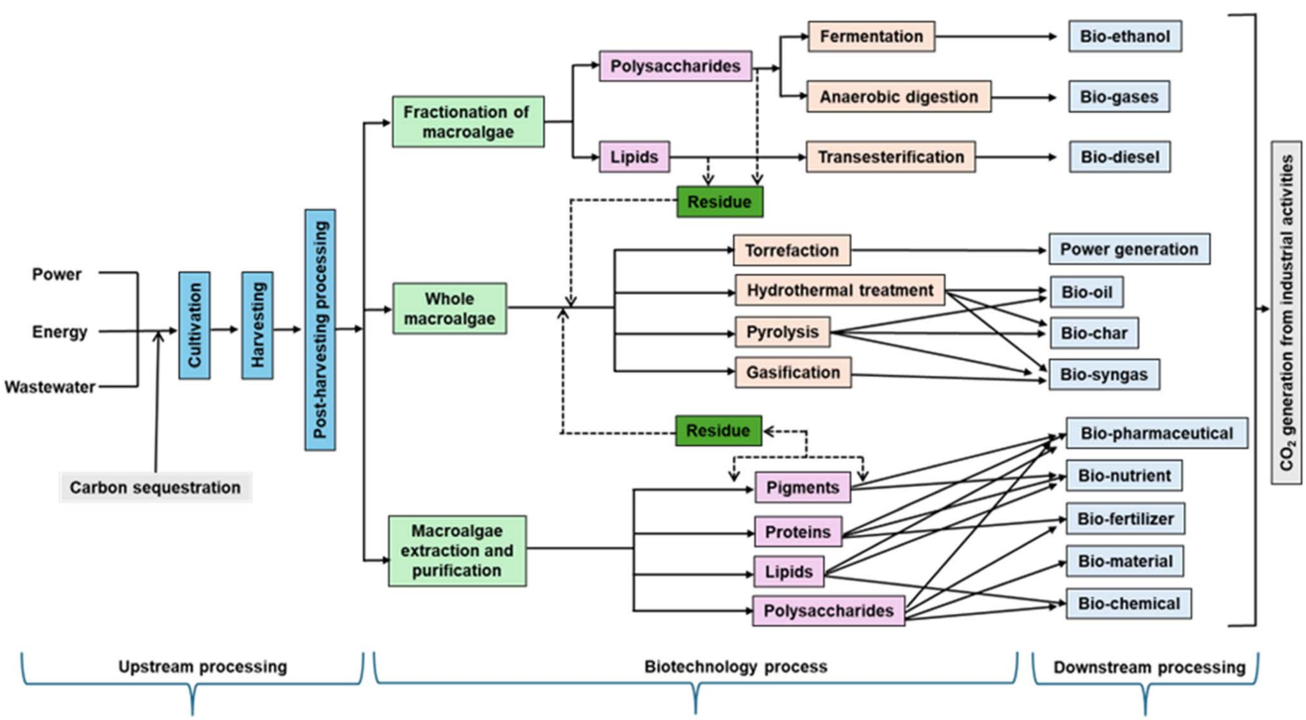

Fig. 4 Schematic representation of the macroalgal biorefinery pathways,.[4] The diagram illustrates the sequential stages from cultivation and harvesting to post-harvest processing, fractionation, and conversion routes for macroalgae. Both whole and fractionated biomass streams can undergo biochemical or thermochemical processes to yield a variety of value-added bio-products, such as bio-ethanol, bio-diesel, bio-oil, bio-char, and bio-syngas, as well as high-value compounds including pigments, proteins, lipids, and polysaccharides. Residues generated from extraction or conversion steps can further serve as feedstocks for energy recovery or the production of biochemicals and bio-materials, ensuring comprehensive biomass utilization within a circular bioeconomy framework, adapted from ref. 4 with permission from Elsevier (Kostas *et al.*, *Renewable and Sustainable Energy Reviews*, 2021), copyright 2026.

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recovered using methyl *tert*-butyl ether (MTBE) extraction, distilled, and hydrogenated catalytically (290 °C, 60 atm) to produce a mixture of alcohols (ethanol, propanol, butanol).[122,123] The VFA pathway is advantageous for producing a broad spectrum of alcohol and intermediates; however, it depends heavily on solvent extraction and energy-intensive hydrogenation. Lastly, the MP converts volatile solids into biogas through complete AD. For example, AD of *Laminaria digitata* can yield 0.3 m^3 CH_4 per kg VS as biogas, which can be combusted to generate 770 kWh electricity per t dry seaweed, with 82% of the electricity sold externally.[124] The MP provides a direct energy route with moderate yields but stands out for its ability to integrate with combined heat and power systems, offering energy self-sufficiency.[125,126] Each technology also recovers digestate solids that could be sold as fertilizer, emphasizing circularity in seaweed biorefineries. Selecting the appropriate pathway depends on the desired product profile, energy requirements, and compatibility with downstream valorization strategies.

3.3.2. Hydrothermal liquefaction (HTL). HTL is currently regarded as an efficient and promising technology for converting seaweed biomass into biofuels and value-added chemicals.[127,128] HTL, a thermochemical conversion process, occurs in water under subcritical conditions where water acts simultaneously as a solvent, reactant, and catalyst, avoiding the latent heat of vaporization at high pressure or temperature. Seaweed, which naturally contains a high moisture content of 80–85% at harvest, can be directly processed into bioactive compounds and fuel using HTL,[129] enabling the conversion of wet biomass without requiring energy-intensive drying. During HTL, the reaction kinetics include several pathways such as depolymerization, monomer decomposition through bond cleavage, dehydration, decarboxylation, deamination, and subsequent recombination of reactive intermediates. The yield and composition of HTL products depend on multiple factors, including the biochemical makeup and physical characteristics of the seaweed feedstock, the type of solvent used, operational parameters, and catalyst presence. Recent studies on HTL of seaweed biomass have reported bio-crude yields of ∼9.8–17.8 wt% (daf) for brown macroalgae, with HHVs in the range 32–34 MJ kg^{-1}.[130] In specialized experiments on *Enteromorpha prolifera*, bio-crude yields as high as ∼33.8 wt% (daf) with HHV ≈ 29.5 MJ kg^{-1} have also been achieved.[131] In addition, significant char fractions (10.9–18.6 wt%, dry) with HHVs from ∼15.7 to 26.2 MJ kg^{-1} have been observed.[130] These co-products (bio-crude, aqueous-phase extracts, and char) support a cascaded valorization approach, improving overall process efficiency and sustainability.[129] Their relevance in a biorefinery context arises from their potential uses, for example, bio-crude as liquid fuel, aqueous co-products for chemical extraction, and char as soil amendments or energy feedstock, thereby contributing to circular economy goals by minimizing waste and maximizing resource recovery.[127,130–132] HTL faces several obstacles to large-scale commercialization, such as difficulties in handling and feeding pressurized biomass slurries, issues related to equipment corrosion, and the formation or precipitation of salts during processing.

3.3.3. Extraction and purification. Extraction and purification processes in seaweed biorefineries focus on recovering high-value fractions that underpin their economic viability. Beyond fuels and bulk materials, seaweed contains proteins, lipids, pigments, polysaccharides, and bioactive compounds that unlock a suite of specialty products. Protein concentrates and hydrolysates from green seaweeds (*e.g.*, *Ulva*) serve as sustainable feed or functional food ingredients rich in essential amino acids.[133] Lipid extracts, although low in quantity, can be channeled into nutraceuticals or pretreated for biodiesel production. Pigments such as chlorophylls, fucoxanthin, and carotenoids not only contribute to photosynthesis but are also valuable antioxidants and colorants for nutraceutical and cosmetic formulations. Bioactive compounds, including fucoidans, phlorotannins, and carotenoids, provide antioxidant, anti-inflammatory, and antiviral properties, linking directly to the functional roles of polysaccharides and pigments shown in Fig. 3. These compounds are typically purified for use in cosmetics, pharmaceuticals, and food supplements. Seaweed biorefineries first target the extraction of high-value polysaccharides, primarily alginate, carrageenan, and agar, from brown, red, and green seaweed, respectively. Alginates obtained from *Laminaria* and *Saccharina* are widely used as thickeners, stabilizers, and gelling agents in food, pharmaceuticals, textiles, and bioplastics.[134] carrageenan, extracted from red seaweeds such as *Kappaphycus* and *Chondrus*, serve as emulsifiers and stabilizers in dairy and meat products as well as in cosmetics and drug delivery systems.[135] Agar, derived mainly from *Gelidium* and *Gracilaria* genera, is used in microbiological media, food processing, and biotechnology applications because of its strong gel-forming properties. This integrated valorization strategy maximizes revenue streams and reinforces the circularity of seaweed biorefineries.[136]

Pre-treatment of seaweed biomass is a critical yet often overlooked stage in large-scale biorefinery operations. Industrial-scale utilization requires the removal of impurities such as sand, silt, epiphytes, inorganic salts (*e.g.*, NaCl, $CaCO_3$), and heavy metals accumulated during cultivation or harvesting.[137] Technologies employed for this purpose include freshwater or seawater washing, flotation separation, mechanical dewatering, and low-speed sedimentation. Some systems use air bubbling or vibratory sieving to dislodge fine particulates. However, these approaches are often energy- or water-intensive and may generate wastewater with high salt and nutrient loads, posing environmental burdens unless properly managed.

Recent studies have highlighted pre-treatment as a grand bottleneck in macroalgal valorization due to variability in feedstock composition and the difficulty in standardizing protocols across regions and species.[138,139] For example, brown seaweeds such as *Saccharina latissima* may require extra washing cycles due to their mucilage content, while red seaweeds like *Gracilaria* may require alkaline conditioning to remove surface-bound phosphorus or sulfate residues.[140,141] The integration of modular, low-energy pre-treatment units into farm-side infrastructure is a priority for scalable biorefinery deployment.

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4. LCA framework and methodology

The LCA framework of seaweed-based biorefineries follows a structured approach to assess environmental impacts across the life cycle of a product or process. LCA is standardized by the International Organization for Standardization (ISO)[142,143] and further supported by the International Reference Life Cycle Data System (ILCD).[144] According to these standards, an LCA typically consists of four core stages: goal and scope definition, life cycle inventory analysis (LCI), impact assessment (LCIA), and interpretation.

In practice, LCAs of biorefineries often face methodological challenges, including limited process data, inconsistencies in system boundary definitions, allocation rules, or functional units, and recurring issues such as defining goal, scope, and functional units; allocating feedstock and co-products; land use assumptions; and modeling biogenic carbon and emission timing.[145] Additional concerns include the selection of impact categories, simplification of feedstock and process models, regional variations, and uncertainties in foreground and background datasets. These challenges can be mapped across different stages of the LCA framework, as illustrated in Fig. 5. This schematic serves as a visual guide to understand where methodological uncertainties emerge, from inconsistent goal definitions to underrepresentation of key environmental impacts and lack of sensitivity analysis. Each stage is critical in shaping the outcomes and reliability of sustainability assessments.

In the goal definition stage, the study must clarify its intended application (*e.g.*, comparing seaweed-based *vs.* fossil-derived bioplastics), system boundary (*e.g.*, cradle-to-gate or cradle-to-grave), and stakeholder audience.[146,147] The choice between attributional LCA and consequential LCA further determines whether the analysis aims to describe the current system or explore broader system-level consequences.[148] Recent studies have expanded traditional LCA by integrating social LCA and prospective LCA frameworks.[149] These approaches assess labor conditions, social equity, and anticipate future impacts, which are increasingly relevant for evaluating seaweed-based biorefineries as part of a sustainable blue economy. Within the inventory phase, process data are collected across major life cycle stages, such as seaweed cultivation, harvesting, biorefinery processing, usage, and end-of-life management. Depending on the study's objective, this data may include energy inputs, chemical use, emissions, and co-product flows.[150]

The impact assessment stage applies characterization models to quantify how emissions and resource flows contribute to environmental impact categories, such as climate change, eutrophication, acidification, human toxicity, resource depletion, and water use. Common LCIA methods include ReCiPe, CML, TRACI, and ILCD,[151–153] each offering different midpoint and endpoint indicators based on geographic focus and methodological assumptions. For example, ReCiPe enables detailed tracking of flows to both human health and ecosystem-level damages.[154]

The interpretation phase of an LCA typically involves identifying environmental hotspots, assessing uncertainties, and conducting sensitivity analyses.[155] However, as observed in the reviewed literature, these steps are often either omitted or inconsistently reported,[156] thereby reducing comparability across studies and weakening the robustness of conclusions. The selection and implementation of methodological elements, such as system boundaries, allocation strategies, and impact assessment methods, must be tailored to the study's goals, data availability, regional specificity, and intended audience.[157] A rigorously designed LCA ensures consistent interpretation of trade-offs and environmental burdens, empowering stakeholders to make evidence-based decisions in sustainable product development, policy-making, and investment planning for seaweed-based biorefineries.[158]

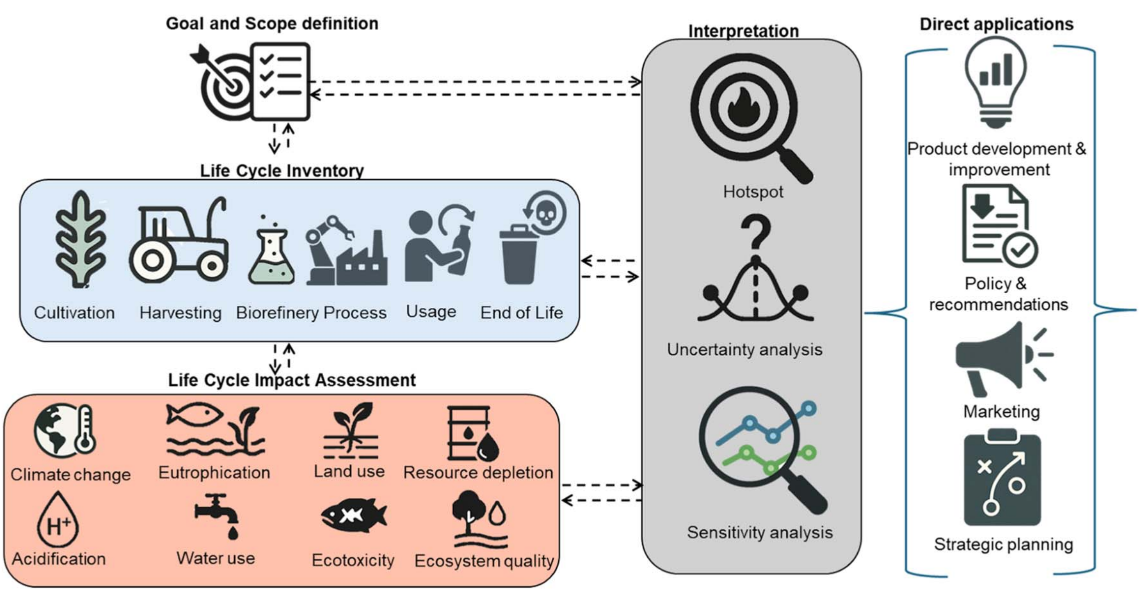

Fig. 5 This schematic outlines the four stages of LCA methodology: goal and scope definition, life cycle inventory, impact assessment, and interpretation. It also highlights downstream applications such as product development, policy design, marketing, and strategic planning.

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4.1. Summary of key LCA studies

In recent years, a growing number of LCA studies have focused on evaluating the environmental performance of seaweed-based biorefineries across various product categories such as biofuels, bioplastics, fertilizers and biostimulants, cosmetics, construction material, protein and feed, food/additive and biochemicals/single cell oil. These studies provide valuable insights into process-level environmental burdens, highlight critical hotspots, and support the identification of opportunities for improvement throughout the life cycle. This section synthesizes key findings from 60 LCA studies, organized by product type, to identify common challenges, methodological trends, and potential strategies for sustainability enhancement within seaweed biorefineries.

4.1.1. Biofuels. Several LCA studies have been conducted to evaluate the environmental impacts of biofuels derived from seaweed, highlighting critical stages and hotspots in the production chain. Aitken *et al.* (2014) investigated the LCA of bioethanol and biogas from brown seaweed in the UK, identifying diesel use and rope production as key contributors to acidification and ozone depletion.[38] In Denmark, Alvarado-Morales *et al.* (2013) assessed biofuels from *Laminaria digitata*, with glycerol use and incineration being major environmental concerns.[39] Brockmann *et al.* (2015) evaluated bioethanol from onshore-cultivated green seaweed in France, pinpointing infrastructure, electricity, and enzyme use as notable hotspots.[40] Similarly, in Italy, Cappelli *et al.* (2015) evaluated a pilot-scale biogas plant co-digesting *Ulva lactuca* with poultry manure, olive mill wastewater, and citrus pulp.[41] While the inclusion of seaweed improved the environmental performance by ∼10% compared to agricultural feedstocks and by 38-fold relative to natural gas, poultry manure management emerged as a major hotspot, accounting for ∼35% of the negative impacts due to ammonia emissions during storage and transport burdens. These finding highlights that, although co-digestion can enhance process stability and valorize multiple waste streams, poorly chosen co-substrates can overshadow the environmental advantages of seaweed. For seaweed-based biorefineries, careful co-feedstock selection and management are therefore critical to ensuring net sustainability benefits In Ireland, Czyrnek-Delêtre *et al.* (2017) focused on compressed biomethane, identifying seaweed drying and combustion as major impact sources.[42] Fasahati *et al.* (2022) in the USA conducted a cradle-to-grave LCA of seaweed-based bioethanol, emphasizing drying as the dominant contributor to environmental impacts.[43] Jung *et al.* (2017) in South Korea identified bioethanol production phase itself as the main hotspot using ReCiPe indicators.[45] Langlois *et al.* (2012) reported that nursery infrastructure and energy demand were key concerns for biomethane production from offshore seaweed in France.[46] Seghetta *et al.* (2016) further expanded biofuel LCAs by framing seaweed biorefineries within regenerative bioeconomy concepts and explicitly modeling biogenic carbon flows. These contributions highlight the importance of methodological choices in capturing the climate impacts of seaweed-based energy systems.[74,75] Quintanar-Orozco *et al.* (2025) demonstrated that pretreatment of pelagic *Sargassum* not only provides sustainable feedstock but also avoids the uncontrolled decomposition of beach-cast biomass, with drying energy and chemical use identified as key hotspots. In a similar context, Kulikova *et al.* (2024) compared pyrolysis and HTL of *Ulva*, showing that pyrolysis performs better in fossil-dominated energy systems, whereas HTL becomes the preferred option when powered by renewable electricity.[50] Solid waste from carrageenan and agar industries has also been investigated as a circular feedstock: Putri *et al.* (2023) found that ethanol production from *Eucheuma* and *Gracilaria* residues was environmentally competitive with terrestrial ethanol, though enzyme production significantly influenced overall burdens.[51] At the biorefinery scale, Kiehbadroudinezhad *et al.* (2023) reported that coupling anaerobic digestion with digestate valorization in a North Atlantic facility achieved up to 99% lower weighted impacts compared to ethanol-dominated routes, primarily due to credits from avoided fertilizer use.[52] Lastly, Wen *et al.* (2022) studied syngas generation from beach-cast seaweed in Sweden, where energy consumption during pyrolysis was the primary burden.[49] These studies show that hotspot identification varies according to feedstock, conversion pathway, and methodological choices, as well as the environmental indicators applied. Drying consistently emerges as a hotspot in ethanol and biomethane systems due to its high energy intensity, while infrastructure dominates offshore cultivation systems because of construction and maintenance requirements. In contrast, co-digestion studies highlight co-substrate management as critical, with impacts driven by ammonia emissions and nutrient handling. The variability of reported hotspots therefore underscores the need for harmonized methodological frameworks and indicator choices to allow meaningful comparison across seaweed-based biofuel.

The most dominant hotspots in seaweed-to-fuel LCA studies are associated with (1) high-temperature processing (HTL, fermentation, *etc.*), (2) feedstock moisture content, and (3) energy source for heating. Moisture reduction prior to HTL can lower GWP by ∼15–25%, depending on the method. Integrated energy recovery systems (*e.g.*, using HTL aqueous phase or digestate) are critical for improving net energy balance. A major unresolved contradiction lies in co-product allocation; studies diverge on whether to allocate emissions based on energy content, mass, or economic value, resulting in large swings in impact results. Sensitivity analyses show energy mix (renewables *vs.* fossil) is the single biggest driver of impact variation.

4.1.2. Bioplastics. A growing body of research has focused on the LCA of seaweed-derived bioplastics and cosmetics to evaluate their environmental sustainability and pinpoint process-level hotspots. In the bioplastics domain, several cradle-to-grave LCA studies conducted in Denmark have consistently identified the crosslinking stage as the most environmentally burdensome, primarily due to its intensive chemical and energy requirements.[18,19,31,32] Chiew *et al.* (2022) examined nanocomposite alginate beads from seaweed in Malaysia for heavy metal removal, identifying alginate extraction and bead transportation as major contributors to environmental impacts.[33] Similarly, Rey (2015) in the USA focused

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on sodium alginate extraction, finding that diesel consumption during both production and transport posed significant environmental burdens.[34] Beyond *Saccharina*, Mohammed *et al.* (2023) examined *Sargassum* alginate composites and revealed that while per-kilogram impacts exceeded those of PLA and PET,[36] a functional unit based on oxygen barrier performance demonstrated dramatic advantages, with 64–978 times lower impacts. Complementary work on a UK marine biorefinery underscored the influence of methodological choices, showing that allocation approach and energy mix can shift results substantially, with economic allocation most favorable.[37] These studies consistently underscore that crosslinking, extraction, and transportation are dominant hotspots in seaweed-based plastic systems, while climate-related impacts such as greenhouse gas emissions are central, other categories are equally critical. For instance, chemical-intensive crosslinking processes contribute to human toxicity and ecotoxicity through solvent and reagent use; energy-intensive extraction drives acidification and eutrophication *via* upstream electricity production; and long-distance transport amplifies fossil resource depletion and particulate matter formation. This suggests that beyond reducing carbon footprints, targeted process improvements, such as greener chemical substitution, renewable energy integration, and localized supply chains, could substantially mitigate a wider range of environmental impacts.

The environmental performance of seaweed-derived bioplastics hinges primarily on three factors: (1) energy use during drying and casting, (2) solvent and crosslinker choices, and (3) film yield per unit of dry biomass. Several studies reported that thermal drying alone can account for up to 50–70% of total GWP and CED. Replacing fossil-based crosslinkers (*e.g.*, glutaraldehyde) with safer alternatives (*e.g.*, genipin) and using renewable electricity for casting processes are strong levers for impact reduction. However, inconsistencies remain in how biodegradability and end-of-life are modeled, some studies assume full compostability, others landfill. Functional unit definition (*e.g.*, 1 kg *vs.* 1 m^2 film) and assumptions about solvent recovery efficiency strongly influence toxicity and energy-related results.

4.1.3. Cosmetics. In order to identify the environmental impacts cosmetics made from seaweed, Pagels *et al.* (2022) from Spain conducted a cradle-to-factory gate LCA on cosmetics derived from red seaweed, identifying the drying phase of the biomass as a significant environmental hotspot.[66] This study highlights the relatively low overall environmental burden of seaweed-based cosmetics compared to conventional formulations, while emphasizing that energy-intensive drying remains a key contributor. Moreover, Arias *et al.* (2025) investigated the extraction of R-phycoerythrin from *Palmaria palmata* and *Sarcopeltis skottsbergii*, demonstrating that enzymatic water-based methods provided the best balance of environmental performance and extraction yield. In contrast, freeze-drying and chemical-intensive methods were identified as hotspots, substantially increasing energy use and associated emissions.[70] These findings point to the potential sustainability of seaweed as a feedstock for cosmetics, especially if energy-efficient or renewable drying technologies are employed.

4.1.4. Fertilizers & biostimulants. Numerous studies have explored the environmental performance of seaweed-based fertilizers and biostimulants, focusing on their potential to reduce greenhouse gas emissions and displace conventional agro-inputs. Anand *et al.* (2018) in India conducted an LCA of *Gracilaria edulis*-derived biostimulants and identified plastic packaging, blow moulding, and electricity use as dominant hotspots, particularly affecting toxicity and energy-related impact categories.[53] Similarly, Ghosh *et al.* (2015) analyzed biostimulant production from *Kappaphycus alvarezii*, reporting electricity-intensive processing stages as significant contributors to environmental impacts.[54] Seghetta *et al.* (2016) in Denmark evaluated seaweed's role in circular nutrient systems, with key hotspots being plastic rope use and nutrient bioextraction.[55] In terms of field-level impacts, Sharma *et al.* (2017) demonstrated that substituting synthetic fertilizers with seaweed-based biostimulants in rice cultivation reduced emissions by 9.5 kg CO_2-eq per ton of production.[56] Singh *et al.* (2023) reported that biostimulants applied in sugarcane fields in India led to 2–3 kg CO_2-eq reduction per ton of cane, largely due to reduced reliance on synthetic fertilizers.[57] Complementing this, Singh *et al.* (2018) showed a more substantial reduction of 260 kg CO_2-eq per ton of cane with seaweed-based fertilizer use, emphasizing the climate mitigation potential of integrating seaweed into conventional farming systems.[58] Arias *et al.* (2024) compared three extraction routes for macroalgal biostimulants and found that conventional thermal processes such as steam autoclaving and boiling yielded the lowest climate burdens (∼0.8 kg CO_2-eq per batch), while supercritical CO_2 extraction was more resource-intensive due to CO_2 compression and elevated energy demand.[59] These studies indicate that while electricity use, packaging, and nutrient extraction can be key burdens, seaweed-based fertilizers and biostimulants consistently demonstrate strong potential to reduce greenhouse gas emissions, displace synthetic agro-inputs, and support more circular and climate-resilient agricultural systems.

What matters for greenness: for seaweed-based fertilizers and biostimulants, environmental impacts are mostly driven by (1) solvent extraction methods, (2) processing energy (*e.g.*, evaporation), and (3) transportation from farm to application site. Studies using water or ethanol as solvents report 20–40% lower GWP and toxicity compared to acid or alkali-based extraction routes. However, allocation methods (especially when fertilizer is a co-product from biorefineries) vary widely, affecting comparability. Another unresolved issue is the end-use modeling, whether benefits such as reduced synthetic fertilizer use or soil health improvements are credited in LCA. Transport distance and bulk density significantly influence outcomes, making moisture content and concentration strategies critical sensitivity levers.

4.1.5. Protein/feed. Several studies have considered using seaweed for protein and feed. Coelho *et al.* (2022) assessed the cross-processing of seaweed and fish side-streams in Sweden, identifying land use and energy demand as key concerns.[62] Halfdanarson *et al.* (2019) in Norway found the drying stage to be the most significant environmental burden in seaweed

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protein concentrate production.[63] Koesling *et al.* (2021) also reported energy consumption as a major contributor across different protein production scenarios.[64] In Denmark, Seghetta *et al.* (2017) examined co-production of biogas and protein, emphasizing the substitution of synthetic fertilizers and fossil energy as beneficial to reducing GHG emissions.[48] Several broader system-level studies also fall into this category. Nilsson *et al.* (2022) presented a biorefinery concept integrating food, materials, and energy.[65] Thomas *et al.* (2022) focused on nutrient loop closure, emphasizing nitrogen and phosphorus recycling.[77] Zhang and Thomsen (2021) combined TEA and LCA to assess sequential extraction of biomolecules from multiple brown macroalgae, showing how feedstock selection influences environmental outcomes.[81] Meité *et al.* (2024) examined the application of *Asparagopsis* as a feed additive in dairy systems and demonstrated enteric methane reductions ranging from 23% to 67%. However, these benefits came with trade-offs, including higher fossil resource depletion and acidification linked to upstream cultivation and slurry emissions.[72] These studies show that while drying and energy use remain persistent environmental burdens in protein and feed production, seaweed-based pathways offer meaningful opportunities to reduce GHG emissions and substitute conventional protein and fertilizer inputs, thereby supporting more sustainable food and energy systems.

Key levers for improving greenness in seaweed-based feed LCAs include (1) drying and pelletizing energy use, (2) farmed *vs.* wild biomass sourcing, and (3) functional substitution assumptions (*i.e.*, replacing what feed?). Farmed seaweed generally shows lower impacts than wild-collected biomass due to more efficient logistics and less variability, though this depends on cultivation method (rope *vs.* tank). End-use assumptions matter greatly, whether seaweed replaces soy, fishmeal, or acts as a methane-reducing additive (*e.g.*, *Asparagopsis*) can change outcomes dramatically. Few studies model land use change (LUC) savings or enteric methane reductions robustly, and this is an area needing clearer assumptions and harmonized methods.

4.1.6. Construction. A LCA study on the construction material was done by Ghose (2022) evaluated the use of seaweed insulation within wood wall structures in Denmark.[60] Over a 50-year life cycle, the use of steel materials in the wall system was identified as the main hotspot, emphasizing that material choices outside the seaweed component can dominate the environmental profile. Lyra *et al.* (2025) incorporated *Sargassum* into lightweight ceramic clay aggregates and found that substitution levels of 20–40% increased porosity and reduced density, while mechanical strength was maintained. Importantly, microwave sintering improved compressive strength by up to 90% compared with conventional kilns, while simultaneously lowering energy demand. Transport and electricity use during sintering emerged as key environmental hotspots, but these could be mitigated through local sourcing and renewable energy adoption.[61] This finding illustrates that the benefits of seaweed-based construction materials depend not only on the properties of seaweed but also on the surrounding system design and material pairings. Also, seaweed insulation has the potential to contribute to sustainable building systems, but its overall environmental benefits are contingent on minimizing high-impact co-materials such as steel, highlighting the need for integrative design strategies in construction applications.

Seaweed's application for construction materials (*e.g.*, insulation, panels) is still emerging, with limited but promising LCA data. The top levers for greenness include (1) binder choice (bio-based *vs.* synthetic), (2) drying and processing energy, and (3) fire retardant or additive selection. Studies using lime or natural clay binders report lower impacts than epoxy- or resin-based systems. However, durability trade-offs and fire resistance remain technical gaps, often leading to conservative assumptions in LCA. The greatest sensitivity comes from functional unit choice (*e.g.*, mass *vs.* thermal insulation delivered over time), which strongly affects results when comparing to mineral wool or fiberglass.

4.1.7. Food/additives. A LCA study on food and additives, Slegers *et al.* (2021) performed a cradle-to-grave LCA in the Netherlands on seaweed used as a salt replacement.[68] The study identified seaweed cultivation and transportation as the primary environmental hotspots, indicating the need for optimization in farming and distribution systems to ensure sustainability in food applications. These results suggest that while seaweed can serve as a sustainable alternative in food applications such as salt replacement, its environmental advantages will only be fully realized if cultivation and distribution systems are optimized to reduce energy use and transportation burdens.

4.1.8. Biochemicals/single cell oil. LCA studies in the biochemical and single cell oil category have explored the sustainability of emerging seaweed-based bioproducts, highlighting significant energy and processing-related burdens. Golberg *et al.* (2021) in Israel assessed a solar-seaweed hybrid biorefinery for the co-production of biofuels and biochemicals, finding energy use to be the dominant contributor to environmental impacts across all categories.[44] In the UK, Parsons *et al.* (2019) evaluated the production of seaweed-derived single cell oils, with fermentation, acid pretreatment, and enzymatic hydrolysis identified as major environmental hotspots.[67] Similarly, Zuhria (2022) in Indonesia investigated carrageenan flour production and reported that the use of coal as boiler fuel and potassium hydroxide in processing were key contributors to the overall environmental footprint.[69] These studies collectively emphasize the need for cleaner energy sources and greener chemical alternatives in seaweed-based biochemical and oil production systems.

4.1.9. Cultivation and processing of seaweed. In addition to product-focused LCAs, several studies have assessed the environmental performance of cultivation systems themselves. These include evaluations of carbon credit potential,[159] methane mitigation benefits,[73] hatchery and preservation burdens,[76] novel impact categories such as sea surface occupation[78] and explorative scale-up scenarios.[79] Zhang *et al.* (2022) further highlighted cultivation as an eco-industrial system capable of nutrient bioextraction and climate mitigation.[80] Cultivation and harvesting practices exert a decisive influence on the sustainability of seaweed-based value chains, with

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Table 3 Overview of reviewed seaweed LCA studies. CC (Climate Change), EU (Eutrophication), AC (Acidification), OD (Ozone Depletion), POF (Photochemical Ozone formation), HT (Human Toxicity), EC (Ecotoxicity), IR (Ionizing Radiation), PM (Particulate Matter), LU (Land Use), WU (Water Use), RUMM (Resource Use, Minerals and Metals), RUF (Resource Use, Fossils), RUM (Resource Use, marine)

Study	Study origin	Seaweed species	Functional unit	System boundary	Allocation method	Product	Impact categories	Hotspot	Green lever
31	Denmark	Brown	1 kg bioplastic film	Cradle to grave	Mass-based allocation	Bioplastic film production	ReCiPe method, CC, OD, IR, POF, PM, AC, EU, EC, HT, RUMM, RUF, WU	Crosslinking chemicals (*e.g.*, glutaraldehyde or glycerol)	Switch to genipin or enzymatic crosslinkers; lower-temperature crosslinking
32	Denmark	Brown	1 kg bioplastic film	Cradle to grave	Mass-based allocation	Bio-based plastic	ReCiPe method, CC	Crosslinking and drying process	Use solar or heat-pump drying; improve film yield per kg of seaweed
33	Malaysia	Brown	1 kg nanocomposite	Cradle to gate	No allocation	Nanocomposite	CC, AC, EC, OD, RUMM, RUF, HT, POF	Alginate extraction and beads transport	Optimize transport logistics; improve yield during extraction with greener solvents
34	USA	Brown	1 kg extracted sodium alginate	Cradle to factory gate	No allocation	Sodium alginate extraction	CML baseline v2.05 method, RUF, AC, EU, CC, OD, HT, EC, POF	Diesel fuel for harvesting and electricity for extraction	Electrify logistics; improve alginate extraction efficiency
18	Norway	Brown	1 kg bioplastic film	Cradle-to-grave	Mass-based allocation	Bioplastic (alginate-based transparent film)	ReCiPe 2016 midpoint (E), 18 impact categories	Glycerol (crosslinking) dominates CC; hatchery electricity; seaweed cultivation inputs; drying energy	Replace glycerol with greener crosslinker (*e.g.*, citric acid); renewable electricity; improve drying efficiency
19	Norway	Brown	1 kg alginate	Cradle-to-grave	Mass-based allocation	Bioplastic films, alginate-cellulose microfibers, PLA composites	ReCiPe 2016 midpoint (E)	Glycerol (film fabrication), $NaHCO_3$ alkaline treatment, electricity in extraction, drying	Replace crosslinker (GC #3, #4); use green reagents; improve drying heat recovery
35	Norway	Brown	1 kg bioplastic film	Cradle-to-grave	Mass-based allocation	Bioplastic film (alginate-based, bio-based & biodegradable)	ReCiPe 2016 midpoint (E), GWP, LU, FRS, WU, HCT, HNCT	Film fabrication (esp. Glycerol: 2.1 kg CO_2-eq per kg film); co-product recirculation needs H_2O_2 & ethanol; EoL scenario (composting *vs.* incineration)	Replace glycerol with low-impact crosslinkers (*e.g.*, citric acid); recover H_2O_2; prioritize composting in EoL scenarios
36	Caribbean (trinidad & tobago, Mayaro/ Chamomile coast)	Brown	1 kg $Ca(Alg)_2$ bioplastic	Cradle-to-gate	Mass-based allocation	Calcium alginate composite bioplastic ($Ca(Alg)_2$)	ReCiPe 2016 midpoint (H)	Chemicals: Na_2CO_3 (10–18%), H_2SO_4 (12–52%), NaOCl (15–22%); energy heating (61% GHG)	Use mild acid/base alternatives; recover energy *via* heat integration; avoid NaOCl by switching to H_2O_2 or filtration

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Table 3 (*Contd.*)

Study	Study origin	Seaweed species	Functional unit	System boundary	Allocation method	Product	Impact categories	Hotspot	Green lever
37	UK	Brown	1 kg packaging material	Cradle-to-gate	System expansion, mass allocation or economic allocation	Protein, fucoidan, laminarin, alginate–cellulose polymeric packaging material	ReCiPe 2016 midpoint (H), 18 impact categories	Filtration wastewater (up to 60% of GWP); HCl in acid extraction (45–97% in several categories); drying (esp. SD3); heating demand	Water reuse in filtration; replace HCl with organic acids; dry *via* low-temperature solar/heat pump
38	UK	Brown	1 MJ of energy	Cradle to factory gate	Energy content-based allocation (based on biogas *vs.* bioethanol energy yields)	Bioethanol and biogas	CC, AC, EU, OD, POF, HT	Diesel fuel during transport and rope materials used in cultivation	Shift to low-impact mooring systems; electrify boats or switch to biodiesel
39	Denmark	Brown	1 ton of dry seaweed biomass (*Laminaria digitata*)	Cradle to factory gate	No allocation	Biofuels	CC, AC, EU	Glycerol in film compounding and incineration of residues	Use greener plasticizers; valorize residues *via* composting or biochar
40	France	Green	Production and combustion of 1 MJ of usable energy in a passenger car engine	Cradle to grave	Energy content-based allocation	Bioethanol	CC, OD, HT, PM, IR, POF, EU, AC, LU, WU, RUMM, RUF	Enzyme production and electricity use in infrastructure	Improve enzyme efficiency; source electricity from renewables
41	Italy	Brown	Generation of 1.02 kWh of electricity and 10.92 MJ of heat, together with 1.86 kg of compost as a co-product from the biorefinery process	Cradle to grave	Mass based allocation	Biomethane production	HT, CC, EC, AC, EU, LU, RUMM	Collection and storage of poultry manure	Poultry manure improve pre-treatment and sanitation of co-substrates; integrate anaerobic digestion with renewable-powered thermal drying for digestate management
42	Ireland	Brown	1 MJ of compressed biomethane	Cradle to gate	System expansion to account for digestate valorization as fertilizer substitute	Biomethane	AC, CC, EU	Digestate handling and field application, a dominant hotspot, causing >80% of eutrophication and acidification impacts	Improve nutrient recovery; optimize digestate reuse in agriculture
43	USA	Brown	1-ton dry seaweed	Cradle to grave	Energy content-based allocation	Seaweed-derived bioethanol	The CML-IA method, RUMM, RUF, CC, OD, HT, EC, POF, AC, EU	Drying of seaweed biomass	Use low-moisture feedstock; integrate waste heat recovery for drying

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Table 3 (*Contd.*)

Study	Study origin	Seaweed species	Functional unit	System boundary	Allocation method	Product	Impact categories	Hotspot	Green lever
44	Israel	Brown	1 ton dried seaweed's product	Cradle to cradle	Not clearly stated, likely system expansion or no allocation since entire system energy is assessed cradle-to-cradle	Assessment of environmental sustainability in solar-based seaweed biorefinery configurations	ReCiPe method, EU, EC, RUMM, AC, WU, CC, OD, HT, POF, PM, IR, RUF	Total energy use in solar-biorefinery system	Increase solar capture efficiency; phase out fossil backup heating
45	South Korea	Brown	1 kL of bioethanol	Cradle to gate	Not explicitly mentioned, assumed mass-based or energy-based allocation between bioethanol and residues	Biofuel production	ReCiPe method, CC	Bioethanol production	Optimize fermentation yields; recover process heat; integrate HTL where viable
46	France	Brown	1 kg fresh weight seaweed	Cradle to farm gate	No allocation; biogenic carbon considered neutral and co-products excluded	Biofuel production	ReCiPe method, CC, RUMM, RUF, OD, HT, EC, POF, AC, EU	Hatchery infrastructure, and energy consumption	Electrify nursery operations; reduce infrastructure material use
47	Mexico (Caribbean coast, Yucatán)	Brown	Flow rate of 40 kg dry per h	Gate-to-gate (oxidative pretreatment process only)	Not applicable, as gate-to-gate study only addresses pretreatment with no downstream products	Pretreated biomass (oxidative delignification for biofuel/bioproduct valorization)	GREENSCOPE (30 environmental indicators), 5 areas: hazardous materials, human health, ecosystem (air, water), process sustainability (solids)	Energy demand (dryer ~50 kWh); hydrogen peroxide use; residual solid stream	Replace H_2O_2 with greener oxidants (GC Principle #3); recover energy from solids (biochar/combustion)
48	Denmark	Brown	1 ha offshore cultivation	Cradle to factory gate	System expansion used to credit protein and nutrient recovery functions	Energy, feed, and protein generation	ReCiPe method, CC, RUF, EU, HT	Substitution of chemical fertilizer and iron bars	Renewable nutrient recovery; switch to low-impact cultivation materials
49	Sweden	Red and Brown	1 MJ product	Cradle to factory gate	No allocation, system boundary ends at pyrolysis product output with no co-product handling	Biofuel from pyrolysis of beach-cast seaweed, syngas	RUF, CC	High ash content in raw biomass reducing efficiency - Energy-intensive drying and pyrolysis steps - Heavy metal (*e.g.*, cadmium) risk in residues/biochar	Explore HTL over pyrolysis; recover energy; remove heavy metals before process

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Table 3 (*Contd.*)

Study	Study origin	Seaweed species	Functional unit	System boundary	Allocation method	Product	Impact categories	Hotspot	Green lever
50	Russia	Green	1 Mg (1000 kg) of fuel produced	Gate-to-gate	No allocation mentioned	Biofuels (liquid bio-oil from pyrolysis & HTL)	ReCiPe 2016 midpoint (H), CC (GWP100), fossil depletion (FD), human toxicity (HTP), ozone depletion (ODP), terrestrial acidification (TA)	Pyrolysis: drying energy (natural gas); HTL: electricity & high-pressure heating; wastewater treatment burdens	Shift to renewable heat (biogas, solar); integrate HTL heat exchangers; valorize aqueous residue
51	Indonesia	Red	1 kg ethanol	Gate-to-gate	Not clearly stated, but likely mass-based or economic allocation between ethanol and solid waste	Bioethanol (3rd-gen, from extraction solid waste)	CC, ADP, ADP fossil, ODP, HT, FET, MET, TET, POCP, AP, EP	Enzyme production (20%), fermentation (75%), electricity (5%)	Optimize enzyme and fermentation yield per unit product; switch to biobased enzyme sources
52	North Atlantic (case: *Laminaria digitata*, Maritimes, Canada)	Brown	1 MJ energy (biofuel) and 1 MJ electricity	Cradle-to-gate	System expansion used to account for co-products (fertilizers, feed, protein)	Bioenergy carriers (biogas, bioethanol, combined) + waste valorization (fertilizers, feed, protein)	IMPACT World+ (midpoint & endpoint, weighted results in EUR2003)	CH_4 leaks in anaerobic digestion; SHF distillation energy; combined burden	CH_4 capture systems, heat recovery in SHF, multi-product valorization to share burdens
53	India	Red	1 kL (1 m3) of *Gracilaria* seaweed extract	Cradle-to gate	No allocation	Environmental cost from Gracillariid seaweed extract, biostimulants	LU, CC, WU, EC, EU, HT, IR, RUMM, PM, OD, POF, AC	Plastic use for packaging and energy-intensive extrusion	Use biodegradable packaging; optimize process heat with renewable energy
54	India	Red	1 kL (1 m^3) of *Kappaphycus alvarezii* sap	Cradle to gate	No allocation	Biostimulant production	LU, CC, RUF, EC, WU, HT, IR, EU, PM, POF AC	Packaging plastic, extrusion, electricity demand	Use biodegradable packaging, solar-assisted extrusion, and cleaner energy grid
55	Denmark	Brown	1 ton dry weight	Cradle to cradle	No allocation	Seaweed for circular nutrient management, fertilizer	ReCiPe method, CML, EU	Plastic ropes and nutrient bio-extraction	Replace ropes with biodegradable alternatives; recover excess nutrients
56	India	Red	1 ton rice	Cradle to rice production	Substitution approach; avoided burden method using CO_2-equivalent of conventional rice inputs	Seaweed as biofertilizer	ReCiPe method, CC, EC, WU, EU, RUF, HT, IR, PM, OD, POF, AC	CO_2-equivalent emissions from conventional rice inputs	Broad adoption of seaweed fertilizer; reduce methane by improved field drainage
57	India	Red	1 ton cane production	Cradle-to-cane production	Substitution/avoided burden; CO_2-equivalent from synthetic nitrogen avoided	Biostimulants for sugarcane production	ReCiPe method, CC, EU, LU, WU	CO_2-equivalent from cane inputs	Promote foliar biostimulant application; replace synthetic N

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Table 3 (*Contd.*)

Study	Study origin	Seaweed species	Functional unit	System boundary	Allocation method	Product	Impact categories	Hotspot	Green lever
58	India	Red	1 ton of sugar cane	Cradle to cane production	Substitution/avoided burden; avoided impact from conventional sugarcane system	Use as fertilizer	ReCiPe method, LU, CC, RUF, EC, HT, IR, EU, RUMM, PM, OD, POF, AC, WU	High GHG from conventional sugarcane systems	Support full substitution with seaweed-derived nutrients
59	Spain	Red	1 batch process (varies by extraction method, *e.g.*, 175–338 kg extract per batch)	Cradle-to-gate	Mass-based allocation (likely, based on batch extract yield distribution)	Biostimulant extracts (for wheat and other crops)	ReCiPe 2016 midpoint (H), 18 impact categories	Electricity and steam use (scenarios 1 & 2); CO_2 compression (scenario 3)	Use heat recovery in extraction; reduce CO_2 compression needs; green solvent alternatives
60	Denmark	Brown	1 square meter of timber wall with 376.5 mm seaweed insulation, evaluated over a 50-year lifetime	Cradle to grave	No allocation	LCA of biobased construction materials	ReCiPe method, EU, CC, LU, RUF, EC	Steel infrastructure in wall panel insulation	Replace steel with bamboo or recycled wood; optimize insulation-to-weight ratio
61	Brazil	Brown	1 m^3 lightweight ceramic aggregate	Cradle-to-gate (clay/sargassum acquisition, prep, sintering; excludes distribution, use, disposal)	No allocation	Construction material (lightweight ceramic clay aggregates with sargassum particles)	ReCiPe 2016 midpoint, 18 impact categories	Electricity for sintering (esp. Conventional ovens), clay extraction, transport of sargassum, land use for drying	Use solar sintering or heat recovery; optimize sargassum transport and drying *via* local sourcing
62	Sweden	Brown	1 kg protein ingredient	Cradle to gate	Mass-based allocation	Protein extraction from herring side streams using antioxidant-enriched co-feedstocks	CC, RUF, LU, RUM	Centrifugation and grinding (high energy use)	Use low-energy dehydration or passive separation techniques; valorize grinding heat
63	Norway	Brown	1 ton seaweed protein concentrate	Cradle to gate	System expansion/substitution (compared with conventional fish feed systems)	Fish feed	CC	Drying process	Use solar or low-energy drying (*e.g.*, heat pump); harvest at lower moisture levels
64	Norway	Brown	1 kg protein	Cradle to gate	Economic allocation among extracted protein fractions	LCA of protein production	CML 2016, CC, RUF, OD, AC, EU, POF, RUMM	Energy use across processing stages	Switch to renewable energy sources and improve process efficiencies
65	Ireland	Brown	1 ton seaweed	Cradle to factory gate	Mixed method (mass-based and economic allocation across full seaweed biorefinery value chain)	Seaweed value chain	ReCiPe method, CC, OD, IR, POF, PM, HT, AC, EC, EU, LU, WU, RUF, RUMM	Fuel consumption, drying, and inoculum tank	Optimize inoculum re-use; low-impact transportation; solar drying

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Table 3 (*Contd.*)

Study	Study origin	Seaweed species	Functional unit	System boundary	Allocation method	Product	Impact categories	Hotspot	Green lever
64	Norway	Brown	1 kg crude protein	Cradle-to-gate	System expansion (compared SPP from seaweed *vs.* soy protein concentrate)	Seaweed protein product (SPP) *vs.* soy protein concentrate (SPC)	CML 2016 midpoint	Drying energy (>60% GWP with fossil gas); protein extraction rate; farm infrastructure lifetime	Improve drying efficiency; recover latent heat; enhance protein yield per biomass; extend infrastructure life *via* modular design
66	Spain	Red	1 kg cosmetic product	Cradle to factory gate	No allocation	Seaweed for cosmetics	ReCiPe method, CC, RUF, RUMM, WU, EU	Drying process	Use waste heat from other processes; explore low-temperature dehydration
67	UK	Brown	1 ton single cell oil	Cradle to factory gate	No allocation	Single cell oil production	Recipe method, CC, EU, HT, EC, AC, WU	Fermentation and acid pretreatment, and enzymatic hydrolysis	Reduce enzyme input *via* immobilization or reuse; integrate renewable heat
68	Netherland	Brown	1 kg salt replacement, processed and packed at supermarket	Cradle to grave	Mass allocation	Use as food ingredients, 100% salt replacement	CC, EU, RUF, WU, LU	Seaweed cultivation (transportation)	Use electric transport options; optimize harvest location *vs.* demand centers
69	Indonesia	Red	1 kg carrageenan flour	Cradle to factory gate	No allocation	Seaweed in carrageenan flour products	CML-IA baseline version 3.06., CC	Carrageenan flour production phase (the use of coal as boiler fuel, potassium hydroxide, and solid waste)	Switch to biomass/solar for steam; reduce chemical inputs *via* green chemistry pretreatment
70	Spain, Estonia, Latvia	Red	Annual catch (464.5 t seaweed) and 1 batch of extraction	Cradle-to-gate (harvesting, transport, extraction, purification up to factory gate)	Economic allocation between pigment (R-phycoerythrin) and residual biomass or alternative extraction outcomes	Pigment (R-phycoerythrin)	ReCiPe 2016 midpoint (H) & endpoint, CC, AC (TA), FE, ME, TET, FET, MET, HCT, HNCT, FRS, SOD	Electricity & steam demand in extraction; freeze-drying; sodium acetate buffer; marine diesel for trawler	Switch to solar-assisted extraction/drying; use low-toxicity buffer alternatives; optimize trawler logistics
69	Indonesia	Red	1 kg carrageenan flour	Cradle to factory gate	No allocation	Seaweed in carrageenan flour products	CML-IA baseline version 3.06., CC	carrageenan flour production phase (the use of coal as boiler fuel, potassium hydroxide, and solid waste)	Switch to biomass/solar for steam; reduce chemical inputs *via* green chemistry pretreatment
71	China	Red	1 kg agar product	Cradle-to-gate	No allocation	Hydrocolloid (agar)	ReCiPe 2016 midpoint (H) + EP&L monetization	Energy & chemicals in agar extraction; activated carbon use	Use green solvents (GC #5); improve efficiency of activated carbon use; valorize side streams

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Table 3 (*Contd.*)

Study	Study origin	Seaweed species	Functional unit	System boundary	Allocation method	Product	Impact categories	Hotspot	Green lever
72	Germany	Red	1 kg fat- and protein-corrected milk (FPCM)	Cradle-to-farm gate	Mass allocation between milk and co-products (*e.g.*, manure, based on nutrient content)	Dairy milk with mitigation measures (seaweed feed, cow toilet, slurry acidification	CML-IA baseline, CC, EP, AP, AD	Enteric CH_4 emissions, manure NH_3 emissions, feed-related impacts	Methane-reducing feed additives (*e.g.*, seaweed); improved manure handling; precision feeding strategies
73	Sweden	Red	1 kg dry seaweed	Cradle to factory gate	No allocation	Environmental impact of seaweed production	CC, AC, EC, EU, HT, RUMM, WU, RUF, OD, POF, IR	Salt use in inoculum tank stage	Substitute or reduce salt input; integrate salt recycling systems
74	Denmark	Brown	1 ha sea surface	Cradle to grave	System expansion (bio-extraction and fuel substitution included)	Offshore seaweed production for biorefinery	ReCiPe method, CC, RUF, EU, HT	Iron bars for cultivation, N & P bio-extraction, substituted gasoline	Use recycled/reused steel; optimize bio-extraction rate; replace gasoline with electricity
75	Denmark	Brown	1 ton dry seaweed (annual production and processing)	Cradle-to-seaweed drying	No allocation	Dry seaweed biomass	ReCiPe method, CC	Drying, fermentation, liquid fertilizer spreading	Use solar/waste-heat drying; reduce nutrient leaching in fertilizer spreading
76	Sweden	Brown	1 ton of fresh kelp	Cradle to grave	No allocation	Comparing methods to preserve seaweed	CML 2 baseline 2000, CC, RUMM, AC, EU, OD, HT, EC, POF, RUF	Equipment production (hatchery, cultivation), the preservation and storage of harvested seaweed, which requires energy for refrigeration and transportation	Reuse/recycle infrastructure; improve preservation with low-temp or solar refrigeration
77	Sweden	Brown	1 kg fresh seaweed	Cradle to farm gate	No allocation	Nutrient uptake potential	CML, CC, EU, RUF	Transport, steel infrastructure, and of polyethylene or polypropylene components	Optimize site location to reduce transport; replace plastics with biodegradable options
78	Belgium	Brown	1 kg fresh weight seaweed	Cradle to farm gate	No allocation	Seaweed production	ReCiPe method, CC, EU	Cultivation infrastructure and energy use	Use renewable energy for pumping/lighting; switch to bio-based ropes and anchors
79	Netherland	Brown	1 ton protein content	Cradle-to-seaweed drying	Mass-based allocation	Sustainable cultivation system for seaweed production	CML 2001 and cumulative energy demand, RUMM, AC, EU, CC, OD, HT, EC, RUF	Drying, and infrastructure (production of the chromium steel chains and polypropylene rope, and infrastructure,	Avoid toxic materials (*e.g.*, chromium steel); use waste heat for drying

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Table 3 (*Contd.*)

Study	Study origin	Seaweed species	Functional unit	System boundary	Allocation method	Product	Impact categories	Hotspot	Green lever
								and drying for toxicity related impacts	
80	Denmark	Brown	1 ha cultivation area	Cradle-to-gate	No allocation	Seaweed as bio-extractor	ReCiPe method, CC, EU	Process heating and product drying	Use low-energy heating and drying (solar, waste heat recovery)
81	Denmark	Red and Brown	1 kg dry matter feedstock processed	Gate to gate	No allocation	Techno-economic and environmental assessment of biorefinery	CC, WU, RUMM	Energy use for heating and drying	Electrify biorefinery with renewables; optimize moisture content before drying
82	China (Dalian, Liaoning)	Brown	1 ton wet seaweed	Cradle-to-shore	No allocation	Seaweed production	ReCiPe 2016 midpoint (H), 18 impact categories	Diesel combustion for marine transport/harvest (~50% CC); polyethylene lines (~28–33%); buoys (~9–12%)	Electrify harvesting; shift to biodegradable/biocomposite ropes and buoys
83	Europe (France, Ireland, Denmark, Sweden)	Brown	1-ton fresh seaweed	Cradle-to-farm gate	No allocation	Seaweed production	ReCiPe 2016 midpoint, CC (kg CO_2-eq), FE (kg P eq), ME (kg N eq)	Plastics (ropes, buoys), metals (anchors, chains), electricity in hatchery; boat fuel (diesel *vs.* tkm modelled)	Replace fossil-derived plastics; integrate renewable electricity; streamline anchor systems
84	Ireland	Brown	1 kg fresh seaweed	Cradle-to-gate	No allocation	Seaweed production	IPCC GWP100, CEENE/CExD (exergy), GWP (kg CO_2-eq)	Wild harvesting: boat fuel (mechanical), cultivation: capital equipment, boat fuel, hatchery energy	Electrify boats; switch to passive intake hatcheries; minimize capital intensity
85	Baltic sea region (Estonia, Iceland, literature-based Denmark)	Red	1 ton fresh seaweed	Cradle-to-gate	No allocation	Seaweed production	Environmental footprint (EF) 3.0, CC, PM, AP, EF (freshwater/marine), ECF, LU, WU, RF, RM&M	Wild harvest (WH): diesel in boats. On-shore cultivation (ONC): electricity for artificial lighting. Off-shore cultivation (OFC): ropes, buoys, boat fuel	Renewable electricity; bio-based cultivation infrastructure; hybrid/methanol boat systems
86	Global	Brown, green, red	1 kg dry macroalgae	Cradle-to-grave	Mass allocation	Integrated (protein, FDCA, Lactic/Succinic acid, salts, nutrients)	CC (GWP), FD, HT, WD (Aquatic ecotoxicity), social impacts	Energy intensive upstream process	External fossil energy for drying/pretreatment

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dies spanning Asia and Europe underscoring strong geographical and methodological variability. Wu *et al.* (2025) compared *Undaria pinnatifida* (wakame) and *Saccharina japonica* in Dalian, China, finding that wakame exhibited 10–40% higher carbon footprints due to lower biomass yields, while farm infrastructure such as ropes, buoys, and anchors constituted substantial contributors in both systems.[82] Thomas *et al.* (2024) harmonized life cycle inventory datasets for European kelp farms and showed that methodological choices, particularly whether transport was modeled as diesel consumption or ton-kilometers, could double reported GHG emissions, emphasizing the need for standardized protocols.[83] In China, Zhang *et al.* (2024) highlighted that in *Gracilaria* agar production, processing stages such as chemical and water use dominated impacts rather than cultivation itself.[71] Vance *et al.* (2023) demonstrated that manual wild harvesting in Ireland was the lowest-impact option but limited in scalability, while large-scale cultivation was more energy- and capital-intensive but created stronger rural employment benefits.[84] Paoli *et al.* (2023) further compared Baltic Sea systems and found that onshore cultivation had the highest impacts due to electricity-intensive pumping and lighting, offshore farms had moderate impacts, and wild harvesting remained most favorable environmentally.[85] Large-scale evidence from Shandong, China (Li *et al.*, 2023) confirmed that commercial kelp farms achieved very low climate intensities (57.5 kg CO_2-eq per t fresh weight), significantly lower than European pilot-scale farms, highlighting the advantages of scaling and efficient farm logistics.[160] Quintanar-Orozco *et al.* (2025) demonstrated that pretreatment of pelagic *Sargassum* not only provides sustainable feedstock but also avoids the uncontrolled decomposition of beach-cast biomass, with drying energy and chemical use identified as key hotspots.[47] Collectively, these findings stress that the sustainability of cultivation systems hinges on yield, scaling, and methodological transparency, with wild harvesting providing a low-impact baseline and offshore/onshore cultivation requiring optimization to remain competitive.

For blue carbon LCAs, the main sensitivities are (1) carbon sequestration assumptions (*e.g.*, burial *vs.* degradation), (2) life span of stored carbon, and (3) system boundaries (farm-gate *vs.* full fate modeling). Studies estimating long-term sequestration from seaweed sinking to the ocean floor show wide variation in permanence assumptions (years to centuries), heavily influencing climate credits. The most critical unresolved issue is methodological standardization, some LCAs use net GHG balances with sequestration credits, while others exclude them entirely due to uncertainty. Sensitivity analyses consistently show that carbon accounting method and system boundary definitions are the largest levers affecting net climate benefit results.

4.2. Cross-cutting findings

The summary of LCA studies (Table 3) includes the applications, functional unit (FU), system boundary (*i.e.*, cradle-to-gate, gate-to-gate, gate-to-grave, cradle-to-grave, and cradle-to-cradle), impact categories, and major environmental hotspots. Reviewed LCA studies on seaweed cultivation and product valorization reveal several key trends. First, most studies adopt a cradle-to-gate boundary for early-stage or intermediate product assessments, whereas cradle-to-grave boundaries are more commonly applied to biofuel and energy-related pathways.[38,39,43] This distinction is important because it influences comparability across studies and determines whether downstream burdens, such as end-of-life management, are captured. Second, climate change (CC) and fossil depletion (FD) are the most frequently reported categories, though other midpoints such as eutrophication (EP), human toxicity (HT), and water depletion (WD) are inconsistently covered.[40,46,49] These biases limit understanding of broader ecological trade-offs, suggesting the need for wider indicator coverage. Third, environmental hotspots are generally concentrated in upstream cultivation (*e.g.*, diesel use, seeded ropes, hatchery inputs) and downstream processing (*e.g.*, drying, extraction energy, solvent use), while fewer hotspots are reported in intermediate stages such as storage or packaging.[31,32] Recognizing this distribution is critical, as it helps practitioners focus modeling efforts on stages with the greatest leverage for impact reduction. Additionally, several studies highlight the influence of methodological choices, including allocation rules, system boundaries, and functional unit definition, on results.[41,42] For LCA practitioners, this underscores the need to clearly justify assumptions and perform sensitivity analyses to ensure robust conclusions. Finally, very few studies integrate social, economic, or prospective aspects, indicating an opportunity for more holistic sustainability assessments of seaweed-based biorefineries that move beyond environmental indicators alone. For example, a key study by Sadhukhan *et al.* (2019) evaluated an integrated biorefinery for the simultaneous extraction of protein, sugar, salt, nutrient, and mineral platforms. This work stands out by combining LCA and TEA with a Social Life Cycle Assessment (S-LCA), demonstrating that integrated marine systems can be economically superior to terrestrial lignocellulosic biorefineries due to lower production costs and higher-value co-products. Their findings highlight that protein, sugar-based chemicals, and inorganic products offer climate change impact savings of approximately 12, 3, and 1 kg CO_2 eq. per kg of product, respectively. Furthermore, their S-LCA identified Indonesia, China, and the Philippines, which represent 93% of global seaweed production, as the regions with the highest potential for 'avoided social impacts' when seaweed-derived products displace animal-based proteins and minerals.[39]

5. Broader impacts, future direction and opportunities

In order to support the transition toward more sustainable and circular seaweed-based biorefineries, this review synthesizes common environmental hotspots and highlights effective mitigation strategies. A critical cross-comparison across product categories reveals that drying and extraction phases are the most frequent contributors to environmental burdens. Transport and infrastructure also play a role, especially in large-scale or offshore systems. The following tables summarize these

Table 4 Hotspot intensity and mitigation levers across nine seaweed-derived product categories. Each cell reflects relative life cycle impact intensity (high, medium, or low) for drying, extraction, transport, and infrastructure. Text within cells highlights the dominant mitigation lever reported across studies

Product category	Drying/dewatering	Extraction/processing (energy & chemicals)	Transport (wet biomass)	Infrastructure (farm/facility)
Biofuels	Mitigation: renewable drying heat	Mitigation: process energy integration	Mitigation: local logistics	Mitigation: durable materials
Bioplastics	Mitigation: renewable drying heat	Mitigation: green solvent substitution	Mitigation: efficient transport	
Biostimulants and fertilizers	Mitigation: solar drying	Mitigation: biodegradable inputs	Mitigation: short-distance delivery	
Protein & feed	Mitigation: renewable drying energy	Mitigation: enzyme optimization	Mitigation: decentralized collection	Mitigation: modular design
Cosmetics	Mitigation: low temperature drying	Mitigation: natural solvents	Mitigation: regional supply	
Biochemicals	Mitigation: low temperature drying	Mitigation: natural solvents	Mitigation: regional supply	
Construction materials	Mitigation: passive drying	Mitigation: low-carbon binders	Mitigation: local sourcing	
Food ingredients	Mitigation: energy-efficient drying	Mitigation: minimal processing	Mitigation: proximal logistics	
Cultivation and processing of seaweed	Mitigation: natural drying	Mitigation: minimal inputs	Mitigation: decentralized hubs	Mitigation: simple structures

High Medium Low

findings and provide a forward-looking roadmap to guide innovation and policy.

Table 4 presents a heatmap of environmental hotspot intensity across nine major product categories, along with the most effective "green levers" observed across studies. Table 5 outlines an actionable roadmap, organized by time horizon, linking each intervention to relevant Green Chemistry Principles. Together, these tools offer a strategic framework for researchers, technologists, and policymakers aiming to align seaweed valorization with climate, circularity, and sustainability goals.

5.1. Sustainability design levers: insights from green chemistry and SDG alignment

The process hotspots and mitigation levers identified across the reviewed LCA studies align with several design strategies rooted in Green Chemistry and the UN (SDGs). For example, replacing toxic organic solvents with ethanol or water-based alternatives (aligned with Principle 5: safer solvents) showed up to 70% reduction in toxicity-related impacts.[32,77] Energy-intensive drying and extraction stages, identified as dominant hotspots, can be addressed by shifting to renewable-powered, thermal systems and decentralized pre-processing units, consistent with Principle 6: energy efficiency and SDG 7 (affordable and clean energy).[43]

Moreover, the use of biodegradable materials and co-product valorization directly supports Principle 10: design for degradation and SDG 12 (responsible consumption & production). In several bioplastic and biostimulant case studies, implementing crosslinkers derived from bio-based inputs reduced global warming potential by 30–60%. These interventions demonstrate the critical role of early design decisions in improving sustainability performance, particularly when supported by consistent LCA data and regional energy profiles.[35]

By embedding these principles into upstream decisions, such as solvent choice, energy source, and end-of-life planning, seaweed-based biorefineries can significantly lower their environmental footprint while delivering on multiple SDG targets including SDG 2 (Zero Hunger), SDG 13 (Climate Action), and SDG 14 (Life Below Water).

5.2. Climate impact: integrating policy relevance and LCA perspectives

Seaweed cultivation and valorization have gained increasing attention as nature-based solutions for mitigating climate change. This is primarily due to their dual capacity for carbon sequestration during growth and displacement of fossil-derived products in various applications, refer Fig. 6.

Although seaweed is widely promoted in policy and research narratives as a sustainable resource, it is essential to rigorously assess and quantify these benefits through LCA. Several studies reviewed in this paper (*e.g.*, ref. 42, 43, 31, and 58) report notable reductions in climate change impact when seaweed-based fuels, bioplastics, and biofertilizers are compared to fossil-based or conventional alternatives. These benefits are often more pronounced when: (1) renewable energy is used in cultivation or drying stages, (2) residues are valorized as co-products (*e.g.*, biofertilizers, feed).

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Table 5 This roadmap outlines near-, mid-, and long-term strategies to reduce the environmental footprint of seaweed-based biorefineries. Priority areas are linked to specific green chemistry principles (P1–P12) and sustainability goals such as GHG reduction, resource efficiency, and system circularity. Actions include adoption of renewable heat for drying, greener solvents for extraction, decentralized preprocessing, standardized modeling practices, and integration of life cycle and techno-economic assessments. The framework aims to guide researchers and practitioners in aligning seaweed valorization systems with green chemistry and sustainable systems design[a]

Time horizon	Priority area	Recommended action/ strategy	Linked principle(s)	Sustainability focus
Near-term (0–2 years)	Drying	Switch to renewable heat sources (biomass, solar, industrial waste heat); apply heat integration where possible	P6 (energy efficiency), P7 (renewables)	GHG reduction, process energy efficiency
	Crosslinking & extraction	Adopt greener solvents/ crosslinkers (*e.g.*, citric acid, ionic liquids); minimize glycerol and toxic agents	P3 (less Hazardous synthesis), P5 (safer solvents & auxiliaries)	Reduced toxicity and eutrophication impacts
	Decentralized processing	Promote on-site dewatering or preprocessing at seaweed farms to minimize transport of water-heavy biomass	P1 (Prevent waste), P2 (Atom economy)	Water-energy nexus, reduced logistics impact
	End-of-life planning	Ensure design for compostability, especially for bioplastics; assess realistic EoL fate (*e.g.*, incineration *vs.* biodegradation)	P10 (design for degradation)	Reduced landfill burden, enhanced circularity
Mid-term (2–5 years)	Modeling standards	Develop standardized FU templates and harmonized system boundaries for biorefineries across LCA studies	P11 (real-time analysis), P12 (inherently safer design)	Inter-study comparability, database improvement
	Indicator set	Move beyond GWP; include acidification, eutrophication, land use, and toxicity indicators as standard	P4 (designing safer chemicals), P12 (safer systems)	More holistic environmental accounting
	Biogenic carbon handling	Integrate time-explicit biogenic carbon modeling with clear assumptions (*e.g.*, temporary sequestration, re-release)	P6 (energy efficiency), P12 (safer systems)	Accuracy in carbon-neutrality claims
Long-term (5–10 years)	LCA-TEA integration	Simultaneously evaluate economic and environmental trade-offs (*e.g.*, low GWP *vs.* high cost of green solvents)	P9 (Catalysis), P12 (system design)	Decision support for commercialization
	Residue cascades	Incorporate multi-output valorization (*e.g.*, protein + biochar + fertilizer) using cascading LCA approaches	P1 (waste Prevention), P2 (Max Atom economy)	Maximizing resource recovery
	Regional siting & logistics	Use spatial LCA models to assess optimal farm and facility locations based on resource availability and impacts	P7 (renewables), P6 (energy efficiency)	Reduced transport footprint, improved siting efficiency

[a] P1-waste prevention, P2-atom economy, P3-less hazardous synthesis, P4-designing safer chemicals P5-safer solvents & auxiliaries, P6-energy efficiency, P7-use of renewable feedstocks, P8-reduce derivatives, P9-use of catalysis, P10-design for degradation, P11-real-time analysis, P12-safer systems design.

Substitution scenarios modeled in various studies demonstrate up to 60–80% of the GHG reduction compared to base scenario,[31] but these results vary significantly depending on assumptions related to: system boundaries (cradle-to-gate *vs.* cradle-to-grave), allocation approaches (economic, mass-based, substitution), biogenic carbon accounting, and energy source used during processing. This variability is important because it shows that reported climate benefits of seaweed biorefineries

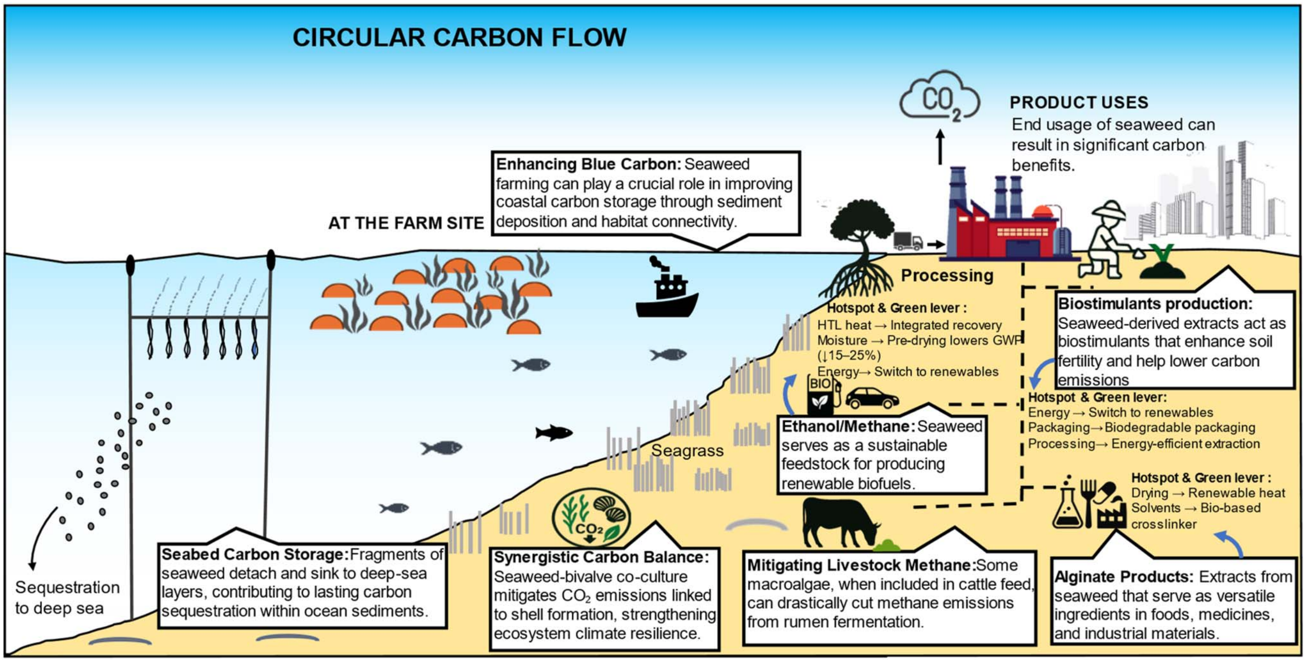

Fig. 6 Schematic of integrated seaweed farming and valorization pathways. Offshore seaweed cultivation can contribute to carbon sequestration through detritus burial in seafloor sediments and, in some cases, export to the deep sea. Cultivation can also support nearby blue-carbon habitats such as seagrass beds. During processing, seaweed biomass yields multiple products, including hydrocolloids (*e.g.*, alginate), proteins, lipids, bio-crude, and aqueous fractions. Valorized uses range from biofuels (ethanol, methane) to biostimulants that improve soil health, and feed additives that can reduce cattle methane emissions. These products can substitute fossil-based alternatives, lowering emissions across sectors. Adopted from ref. 161 (Jones *et al.*, *BioScience*, 2022), licensed under CC BY 4.0.

are highly sensitive to methodological choices, making transparency and harmonization in LCA critical for producing results that can reliably inform policy and industrial decision-making.

Although many studies show that seaweed biorefineries can help reduce greenhouse gas emissions, there are still important gaps in how these benefits are measured in LCA. For example, most studies do not clearly show how carbon captured by seaweed is stored in the long term, such as in soils, sediments, or durable bioproducts. Also, methods like modeling how carbon emissions change over time or vary by location, commonly used in land-based biomass LCA, are rarely applied to marine systems. Because of this, results from different studies can be hard to compare, and the true climate benefits of seaweed might be underestimated.

To improve future LCAs, researchers should consider tracking carbon overtime (*e.g.*, how long it stays stored) and modeling the products replaced by seaweed (*e.g.*, fossil-based plastics or synthetic fertilizers) under what real-world conditions. Adding these elements would make the climate impact assessments of seaweed more reliable and would also provide evidence for policymakers considering blue carbon strategies. However, it is important to note that product substitution credits are not commonly recognized in carbon credit markets due to challenges in verifying counterfactual baselines; instead, such benefits are typically addressed through LCA studies or national greenhouse gas. Fig. 7 illustrates the multifaceted ecosystem services of seaweed cultivation and their alignment with various SDGs, highlighting the environmental, social, and economic co-benefits that warrant future inclusion in LCA frameworks.

5.3. Industrial/technology advancement

The development of seaweed biorefinery technologies is driving innovation at the forefront of the global bioeconomy. These technologies enable the conversion of seaweed into a diverse portfolio of bio-based products, including food ingredients, pharmaceuticals, cosmetics, biofuels, bioplastics, and biostimulants.[162] Evidence from recent LCA studies reviewed in Section 4 shows that industrial and technological advances will be most impactful in addressing recurring hotspots such as energy-intensive drying, chemical crosslinking, and electricity-dependent processing stages. For example, bioplastic LCAs highlight crosslinking as a dominant burden,[32] while biofuel pathways consistently identify drying as the main contributor to climate impacts.[43] Similarly, biostimulant production studies reveal that electricity use during extraction remains a critical challenge.[53,54] Addressing these bottlenecks through innovations in processing methods and integrated valorization strategies could significantly improve energy efficiency and product yield while reducing waste and emissions.[163] This growing industrial relevance is drawing attention from policymakers, investors, and entrepreneurs. The combined economic and environmental potential of seaweed-based technologies positions them as key enablers of the UN Sustainable Development Goals, particularly SDG 9 (Industry, Innovation, and Infrastructure) and SDG 12 (Responsible Consumption and Production).[164,165] Continued investment in seaweed innovation ecosystems is expected to accelerate the transition toward a more circular, inclusive, and low-carbon industrial landscape.

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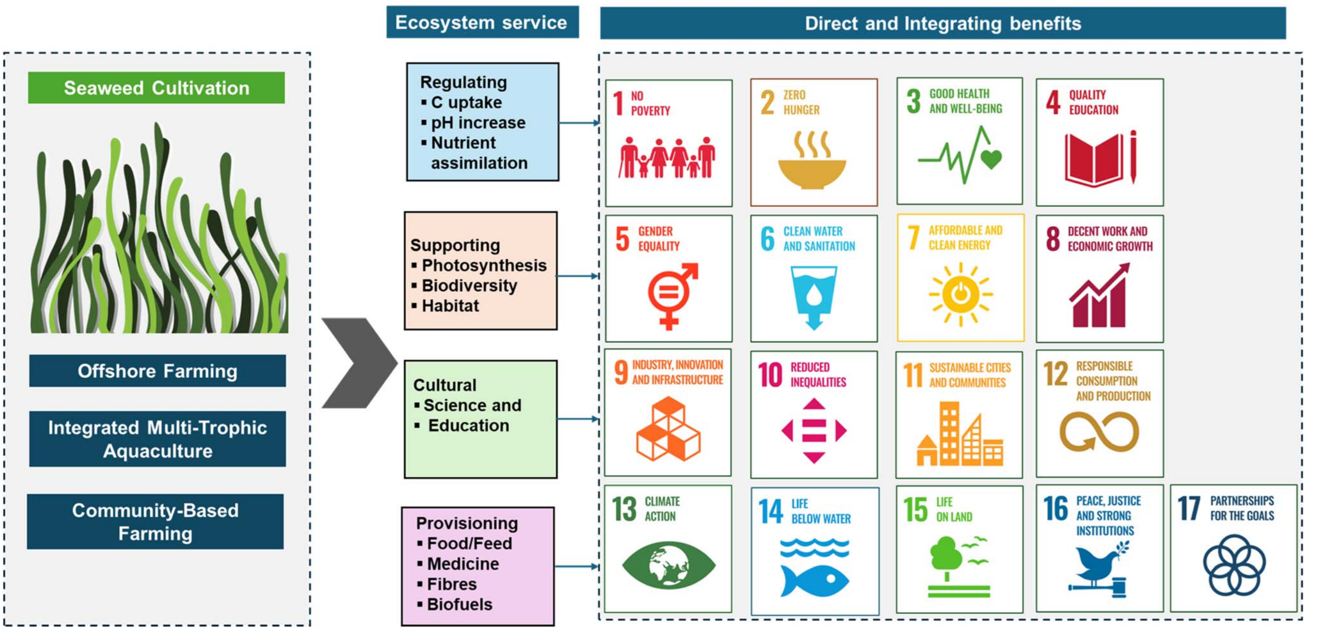

Fig. 7 Seaweed production and utilization contribute to multiple SDGs. Future LCA frameworks should quantify these contributions across environmental, social, and economic dimensions to support broader systems modeling.

5.4. Circular bioeconomy

A circular economy aims to maximize the value extracted from natural resources while minimizing waste and environmental impact.[166] In the context of seaweed, this means leveraging its renewable nature to create value-added products while ensuring that waste materials are minimized, reused, or recycled. Fig. 8 illustrates how seaweed biorefineries connect three functions: a bio-based economy (primary products such as polysaccharides, proteins, lipids, biofuels, and bioplastics), a circular economy (reuse, recycling, and cascading of residues), and a green economy (ecosystem services such as carbon uptake and nutrient removal). Our review shows these benefits are pathway-specific: cultivation often provides measurable ecosystem services, yet many LCAs report that energy and chemical-intensive processing steps (*e.g.*, drying, extraction, and crosslinking) and long-distance transport can significantly reduce or erase net gains (see Sections 4.2–4.4 and Table 3). In contrast, integrated biorefinery approaches that valorize multiple fractions and route residues to anaerobic digestion, soil amendments, or feed generally show better environmental and economic outcomes because of co-product credits and internal energy recovery.[87] To realize the promise shown in Fig. 8, research and policy should prioritize integrated processing, reductions in processing energy and chemical use, and regionally optimized supply chains. This will reduce waste and help seaweed systems truly benefit the environment.

5.5. Challenges

Building on the synthesis of LCA studies presented in Section 4.1 and Table 3, several systemic and technical challenges still hinder the commercial deployment of seaweed biorefineries. These are discussed as follows.

5.5.1. Lack of industrial-scale demonstration and TEA validation. While 60 LCA studies have evaluated the environmental impacts of seaweed-derived bioproducts, the majority focus on lab-scale or pilot-scale processes with limited TEA. This gap in industrial-scale validation introduces uncertainty around scalability, real-world process yields, and profitability, challenges also echoed in the literature.[31,43,44,65,68,75,80] Several reviewed studies highlight drying, crosslinking, and extraction as energy-intensive stages; however, few assess whether these processes are commercially feasible or economically viable under industrial conditions. Bridging this gap requires integrated TEA alongside LCA to support investor and policy confidence.[167]

Future research must prioritize integrated LCA-TEA studies that utilize industrial-scale data to provide decision support for investors and policymakers. Evaluation of "sleeping giant" chemicals like FDCA should be a priority given their high market value compared to bioethanol.

5.5.2. High moisture content and logistics burden. Seaweed's intrinsic moisture content (typically 80–88%) significantly increases the energy demand for drying, as frequently identified in LCA studies across various applications *e.g.*, ref. 42, 43, 46, 56 and 58 The drying stage alone has emerged as a recurring environmental hotspot, particularly for biofuel and bioplastic pathways. Additionally, transportation of wet biomass from remote or offshore sites contributes heavily to fossil energy use and GHG emissions. Addressing this challenge may involve on-site partial dewatering or decentralized pre-processing hubs to reduce mass and improve logistical efficiency.

Future studies should investigate decentralized preprocessing hubs at the farm site to perform partial dewatering. Implementing solar-assisted drying or heat integration can reduce GWP by up to 25%.

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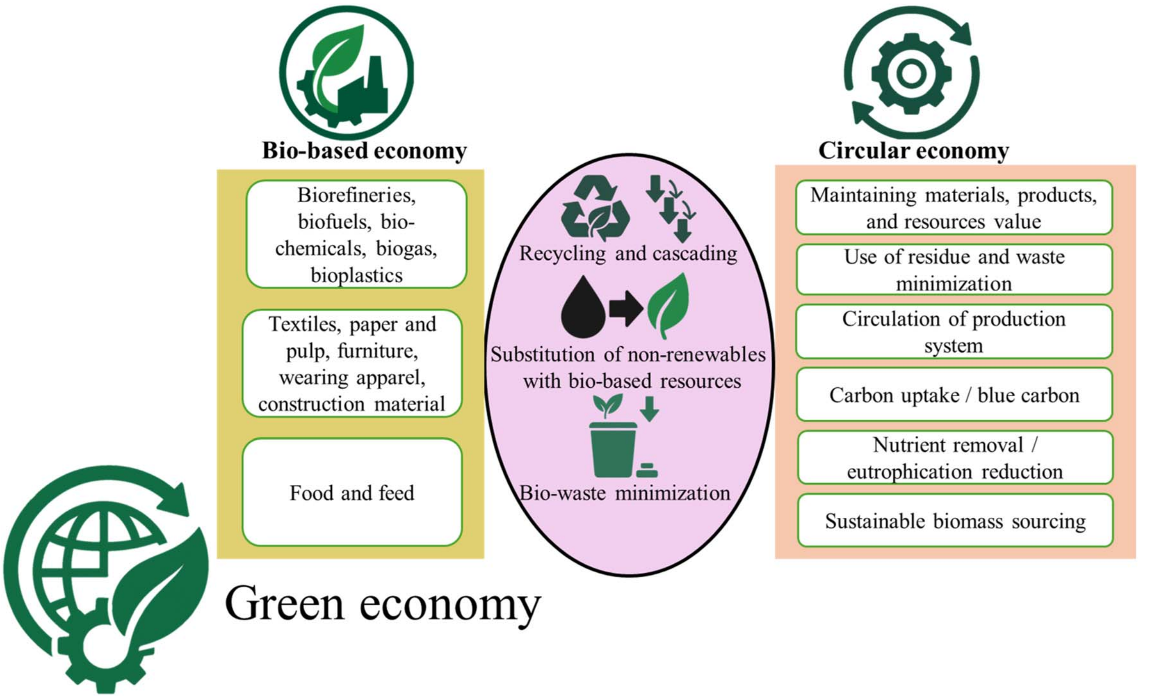

Fig. 8 Relationship between bio-based, circular, and green economy functions for seaweed. Left (bio-based): primary product streams and sectors (polysaccharides, food & feed, biofuels, bioplastics, industrial materials). Centre (circular): strategies to retain value and close loops (recycling, cascading, residue valorization, internal energy recovery). Right (circular/green overlap shown): circular strategies and ecosystem services (maintaining product value, residue reuse, carbon uptake/blue carbon, nutrient removal, sustainable sourcing).

5.5.3. Process compatibility constraints due to ash and salt content. Several seaweed species contain high ash (12–46%) and salts, which complicate thermochemical routes such as combustion, gasification, and HTL. Process studies report salt precipitation and corrosion risks in seaweed HTL and indicate the need for pretreatment, materials selection, and possibly material innovation to improve process compatibility.[130,131] The few LCA studies that include HTL also show that results are highly sensitive to assumptions on ash/salt handling and upstream energy use.[50]

Future work will help to developing cascading extraction protocols to remove salts and minerals before energy conversion can turn these impurities into secondary revenue streams.

5.5.4. Feedstock supply insecurity and seasonality. Many regions, especially in the Indian subcontinent, rely heavily on wild-harvested biomass, which leads to seasonal availability and inconsistent feedstock supply. Studies assessing cultivation,[53,82,83] report that seaweed yield and quality vary with temperature, nutrient levels, and harvest time, all of which affect downstream conversion efficiency and LCA results. Zhang *et al.* (2022) further emphasized that cultivation systems can act as eco-industrial production models, providing co-benefits such as nutrient bio-extraction and eutrophication mitigation.[80] To ensure continuous and reliable feedstock flow, there is a need to scale up aquaculture systems and develop localized farming models tailored to regional ecological and economic conditions.

Future work can include large-scale aquaculture expansion, and the development of low-energy preservation methods (*e.g.*, ensiling) are required to ensure a stable, year-round feedstock supply.

5.5.5. Fragmented systems approach and lack of integration. A recurring limitation across the reviewed studies is the lack of integration between upstream and downstream subsystems, leading to oversimplified sustainability assessments. For instance, several cradle-to-gate studies fail to consider the cascading use of biomass, valorization of side streams, or the interdependency between energy self-sufficiency and process economics,[33,34,39] are critical to advancing seaweed biorefineries from conceptual models to commercially viable circular systems.[67,69,168] Addressing these challenges through integrated LCA–TEA studies, improved cultivation practices, pretreatment strategies, and harmonized system modeling is critical to move seaweed biorefineries from experimental concepts toward industrial-scale, commercially viable, and environmentally sustainable solutions.

A key methodological challenge observed across reviewed studies involves the treatment of biogenic carbon within cradle-to-gate boundaries. While seaweed cultivation systems sequester atmospheric CO_2 *via* photosynthesis, most studies either assume carbon neutrality at the gate or omit downstream emissions, potentially overestimating climate benefits if the biomass is rapidly combusted or decomposed. This is particularly problematic when biogenic CO_2 uptake is accounted for as a negative flow (−1), but end-of-life emissions (+1) occur faster than biomass regeneration, creating a temporal mismatch.[20] Future LCA studies of seaweed-based biorefineries should clearly state carbon accounting conventions, adopt consistent system boundaries, and where possible, implement time-differentiated modeling approaches such as dynamic LCA or GWP to better capture the climate relevance of short-lived biogenic carbon

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flows. Also, future frameworks should adopt "Triple Bottom Line" sustainability assessments, integrating LCA, TEA, and Social LCA, to quantify holistic benefits like "avoided social impacts" from displacing fossil-derived products.

Overall, this review highlights that seaweed biorefineries hold strong potential to contribute to the circular bioeconomy by providing low-carbon fuels, materials, and agricultural inputs. While LCA studies consistently identify hotspots such as drying, extraction, and transport, they also demonstrate opportunities through co-product valorization, nutrient recycling, and substitution of fossil-based products. Future research should prioritize industrial-scale validation, integration of techno-economic and social dimensions, and broader coverage of impact categories to establish seaweed biorefineries as robust pathways for sustainable development.

5.6. Guidelines for greener seaweed biorefineries

Across the reviewed literature, certain product pathways (*e.g.*, biostimulants, fertilizers) and process configurations (*e.g.*, solar-assisted drying, mechanical dewatering) consistently demonstrate more favorable environmental profiles. Biostimulants and fertilizers derived from minimally processed seaweed biomass tend to yield the lowest environmental burdens, primarily due to the avoidance of energy-intensive drying, solvent use, or chemical extraction. In contrast, biofuels and bioplastics typically exhibit higher impacts due to extensive downstream processing, though their net climate benefits may improve when paired with renewable energy sources and green solvents.

From a technological standpoint, modular and decentralized biorefineries co-located with cultivation sites can significantly reduce transportation energy and water–energy trade-offs. Key enabling technologies include mechanical dewatering, low-temperature drying, and non-toxic extraction solvents. Among biorefinery integration strategies, multi-product cascading systems that extract both high-value (*e.g.*, protein, pigments) and low-value bulk products (*e.g.*, alginate, biochar) from the same biomass stream offer promising routes toward resource efficiency and climate mitigation. For example, combinations such as biostimulants and fertilizer, alginate and biofuel, protein, pigments, and bioplastics deserve further LCA-informed exploration.

In order to advance the field, future studies should prioritize multi-product biorefineries under harmonized system boundaries and functional units, ideally supported by scenario analysis. Ultimately, the most environmentally beneficial designs will strike a balance between ecological sustainability, economic feasibility, and circularity, tailored to coastal geographies where seaweed thrives.

Conflicts of interest

The authors declare no conflicts of interest.

Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.

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