

Review

Synergistic Conversion and Catalytic Upgrading of Seaweed Biomass for Sustainable Bioenergy: Advances, Challenges, and Future Prospects

Qing Xu ^{1,2}, Shenwei Zhang ^{1,2} and Shengxian Xian ^{1,2,*}

¹ College of Ocean Engineering and Energy, Guangdong Ocean University, No.1, Haida Road, Zhanjiang 524088, China; xuqing-zj@163.com (Q.X.); zshenwei1999@outlook.com (S.Z.)

² Guangdong Provincial Key Laboratory of Intelligent Equipment for South China Sea Marine Ranching, Zhanjiang 524088, China

* Correspondence: xianshengxian@gdou.edu.cn

Abstract

Seaweed holds significant promise as a renewable feedstock for bioenergy due to its rapid growth, carbon sequestration capacity, and non-competition with terrestrial agriculture. This review examines recent progress in multi-method synergies for optimized energy conversion from seaweed biomass. Physical pre-treatments (e.g., drying, milling, ultrasound, microwave) enhance substrate accessibility but face energy intensity constraints. Chemical processes (acid/alkali, solvent extraction, catalysis) improve lipid/sugar recovery and bio-oil yields, especially via hydrodeoxygenation (HDO) and catalytic cracking over tailored catalysts (e.g., ZSM-5), though cost and byproduct management remain challenges. Biological methods (enzymatic hydrolysis, fermentation) enable eco-friendly valorization but suffer from scalability and enzymatic cost limitations. Critically, integrated approaches—such as microwave-solvent systems or hybrid thermochemical-biological cascades—demonstrate superior efficiency over singular techniques. Upgrading pathways for liquid bio-oil (e.g., HDO, catalytic pyrolysis) show considerable potential for drop-in fuel production, while solid-phase biochar and biogas offer carbon sequestration and circular economy benefits. Future priorities include developing low-cost catalysts, optimizing process economics, and scaling synergies like hydrothermal liquefaction coupled with catalytic upgrading to advance sustainable seaweed biorefineries.

Keywords: seaweed biomass; bioenergy conversion; bio-oil upgrading; sustainably energy



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1. Introduction

Amidst the escalating global energy demands and the ongoing depletion of fossil fuels, the pursuit of renewable and environmentally sustainable alternative energy sources has emerged as a critical objective for scientists and policymakers worldwide [1]. Seaweed has garnered significant attention as a potential source of bioenergy due to its relatively high biomass content, rapid growth characteristics, and broad geographical distribution [2]. Compared to traditional terrestrial biomass feedstocks, such as crop straw or wood, seaweed cultivation does not compete for valuable arable land [3,4]; does not require freshwater resources [5]; and, significantly, absorbs substantial amounts of carbon dioxide during its growth cycle, thus offering potential advantages for mitigating greenhouse gas emissions [6]. Furthermore, the abundant composition of polysaccharides, proteins, and

lipids in seaweed renders it a promising renewable resource for diverse applications and further development [7].

Significant progress has been achieved in the energy-oriented utilization of seaweed, building upon established physical, chemical, and biological processing methodologies. For instance, physical pretreatment via strategies such as drying and grinding significantly reduces moisture content, thereby enhancing the combustion properties of the derived fuel [8,9]. Meanwhile, chemical conversion approaches, including acid/alkali treatment or solvent extraction, are employed to augment the overall efficiency of energy conversion [10,11]. Biological transformation techniques, such as enzymatic hydrolysis and microbial fermentation, effectively decompose complex seaweed constituents into simpler, readily convertible substances [12,13]. Nevertheless, each of these methods, when applied practically, is confronted with distinct limitations, such as high energy consumption, elevated operational costs, or inherent technical complexity, rendering it difficult to simultaneously optimize processing efficacy and cost-effectiveness [14,15]. Furthermore, while upgrading techniques like pyrolysis and gasification can substantially improve fuel quality [16], the scaling up of these technologies remains challenging due to prevailing cost constraints and complex operational requirements.

The escalating recognition of seaweed as a renewable resource distinguished by its high biomass content has positioned it prominently within contemporary bioenergy research. Seminal publications consistently prioritize physiochemical and biological processing methodologies to augment energy conversion yields. However, conventional reviews predominantly focus on single-technology approaches, neglecting critical evaluation of synergistic methodologies, technological refinements, or techno-economic viability. With catalyst innovations and microwave- and ultrasound-assisted technologies diversifying the processing landscape, these emergent techniques have not been comprehensively analyzed in existing critical syntheses. To address this gap, the primary objective of this review is to critically examine recent advances in multi-method synergies for optimized energy conversion from seaweed biomass, with a specific focus on integrated physical, chemical, and biological strategies. This approach distinguishes itself from previous reviews by providing a holistic analysis of synergistic processes, catalyst applications, and techno-economic viability, thereby offering novel insights into sustainable bioenergy production. Therefore, this study systematically analyzes cutting-edge developments and unresolved challenges in algal bioenergy conversion, ultimately proposing actionable optimization pathways to advance its implementation within sustainable energy frameworks.

In contrast to existing reviews, the novelty of this work resides in its holistic synthesis of synergistic conversion strategies—including hybrid physical-chemical-biological systems, chemical catalytic processes, and microwave- or ultrasound-assisted technologies—for enhanced bioenergy yield from seaweed, coupled with an in-depth appraisal of emerging catalytic upgrading pathways such as hydrodeoxygenation and catalytic cracking for liquid bio-oil. This review uniquely integrates progress at molecular and process scales to establish a framework for sustainable seaweed biorefineries, emphasizing scalability and techno-economic feasibility beyond isolated technological reviews.

2. Algal Bioenergy Processing Methods

Figure 1 illustrates the three primary processing directions—physical, chemical, and biological—that structure the conversion approaches discussed in this section.

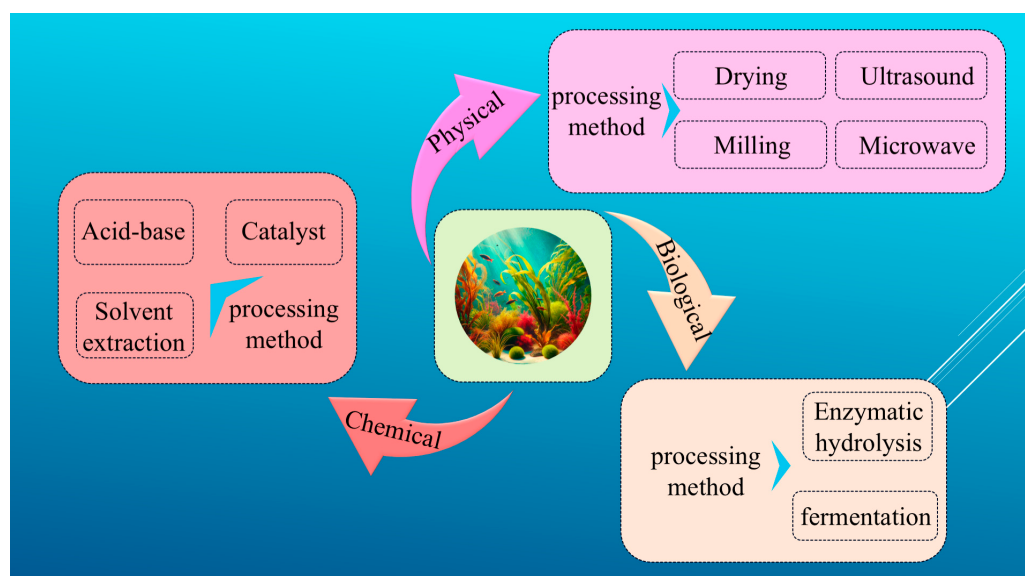


Figure 1. Three processing directions of algae.

2.1. Algal Physical Processing Methods

The characteristically high moisture content inherent in raw seaweed feedstock compromises combustion efficiency if utilized without pretreatment, thereby diminishing the feasibility of subsequent upgrading and valorization approaches [17]. Drying serves as an essential physical preprocessing step designed to remove water, enhancing both energy density and critical fuel properties. Conventional drying techniques comprise solar drying and mechanical dehydration systems. While solar drying offers minimal energy requirements, its low production efficiency and susceptibility to meteorological conditions constrain application primarily to moisture reduction below 22%—a threshold that optimizes transport logistics and handling economics [18]. Conversely, mechanical methods (e.g., roller drying and spray drying) deliver rapid processing and consistent product quality at the expense of substantial energy input; their implementation thus remains economically viable only through extensive operational scaling to achieve cost amortization [8].

Drying pretreatment not only substantially decreases the moisture content of raw feedstock and associated transportation costs but also significantly enhances combustion behavior and gasification efficiency. Empirical studies corroborate that thermally treated seaweed demonstrates measurably higher energy yield profiles during thermo-conversion processes [19]. Crucially, the selection of drying methodology exerts considerable influence on compositional preservation efficiency. Comparative analysis reveals that direct thermal drying, despite inducing partial polysaccharide degradation, achieves approximately 10-fold higher glucose concentrations relative to lyophilization protocols [20]. Concurrently, strategic particle size topology optimization contributes to superior resource utilization efficiency. As referenced by Tedesco et al., methane production potential increases by approximately 53% when particulate fractions are reduced to a specification where 80% of the material possesses a particle size below 1.6 mm [21].

Milling constitutes a paramount post-drying phase, enhancing the efficiency of subsequent thermochemical or biological conversion processes through targeted particle size reduction and amplification of specific surface area [22]. Empirical investigations substantiate that controlled comminution augments combustion performance and reaction kinetics; however, excessive micronization substantially elevates energy expenditure, necessitating a strategic equilibrium between particle refinement and operational energy demand [23].

In landmark research by Schultz-Jensen et al., milling pretreatment markedly elevated macroalgal biofuel yields: integrated wet oxidation (WO) and ball milling (BM) protocols demonstrated optimal ethanol productivity at 44 g ethanol per 100 g glucan—representing a 64% enhancement relative to untreated biomass [24].

Milling combined with other methods can further optimize component separation and utilization efficiency. For example, Alavijeh R S achieved efficient separation of lipids, proteins, and carbohydrates through bead milling for cell wall disruption combined with enzymatic hydrolysis technology, significantly increasing lipid and protein recovery rates [25]. Schwenzfeier A's research demonstrates that ball milling combined with ion exchange chromatography effectively isolates soluble proteins from microalgae [26]. Postma P R optimized ball milling conditions by adjusting biomass concentration and agitation speed, achieving mild disruption of microalgae cells and high-efficiency release of soluble proteins [27].

Different seaweed species respond differently to milling processes. Taleb screened 14 microalgae and found that two species achieved cell disruption rates of 69% and 98% under high-pressure ball milling (1750 bar), showing their potential application in biodiesel production [28]. Overall, drying and milling, as fundamental physical pretreatment steps, significantly enhance the energy conversion efficiency of seaweed biomass, thereby providing favorable conditions for downstream processing [29,30].

Ultrasound and microwave-assisted processing serve as emerging physical pretreatment technologies that significantly enhance algal conversion efficiency by improving cell wall disruption efficiency and promoting mass transfer [31,32]. Ultrasonic processing utilizes the cavitation effect generated by high-frequency oscillation to rupture cell walls, enhancing the release efficiency of polysaccharides and lipids and thereby advancing biofuel production [33]. Under optimized power and treatment time conditions, ultrasound achieves high-efficiency extraction while reducing temperature requirements and energy consumption. Rahman et al. summarized various microalgal cell disruption technologies, noting ultrasound's significant advantages in disrupting rigid algal cell walls and enhancing lipid recovery [34].

Different algae exhibit significant response variations to ultrasonic treatment. Natarajan discovered that cell disruption efficiency correlates positively with energy consumption, and cell wall characteristics significantly affect lipid release [35]. Hao demonstrated through simulation research that optimizing temperature, pressure, ultrasonic power, and frequency can effectively rupture cell walls and promote lipid release, simultaneously improving microalgal oil extraction, thereby providing high-quality raw materials for subsequent hydrogen production [36].

Microwave-assisted treatment utilizes its efficient and uniform heating characteristics to rapidly elevate the permeability of algal cell walls through rapid heating, accelerating component release and conversion [31]. Compared to traditional heating methods, microwave technology rapidly transfers energy, reduces processing time, and lowers energy consumption—particularly effective for seaweed with high moisture content—significantly improving lipid extraction rates and enhancing energy utilization efficiency. Cheng et al. efficiently produced biodiesel via microwave radiation through direct transesterification of wet microalgae, simultaneously achieving significantly improved conversion efficiency from algal residues to bio-crude oil during hydrothermal liquefaction [37].

Zheng compared multiple cell disruption methods (such as grinding, ultrasound, ball milling, enzymatic hydrolysis, and microwave), finding that microwave demonstrated outstanding performance in lipid extraction, particularly suitable for biodiesel production [38]. Teh Y Y's research indicates that microwave-assisted acid hydrolysis not only enhances

sugar recovery efficiency but also generates high-quality biochar. Experimental results reveal that optimizing heating time and temperature can significantly improve energy conversion efficiency [39].

Microwave-assisted treatment can be combined with other methods to further enhance efficiency. For example, Wahidin utilized combined microwave heating with ionic liquids, optimizing reaction conditions via response surface methodology, achieving 42.22% biodiesel yield [23]. Iqbal employed microwave-assisted extraction coupled with co-solvent methods, significantly improving lipid extraction efficiency [40]. Biller research demonstrates that microwave radiation as a pretreatment step for hydrothermal liquefaction effectively disrupts microalgal cell walls, enhancing lipid and phytochemical extraction, while simultaneously exerting significant impacts on carbon, nitrogen, and total mass recovery rates [41].

In summary, physical treatment methods such as drying and milling serve as fundamental pretreatment technologies that enhance seaweed energy density while reducing transportation and processing costs [42]. However, they fail to fully release intracellular biomass resources and cannot function as standalone core approaches for energy-oriented utilization. Although microwave and ultrasonic-assisted treatments demonstrate distinct advantages in cell wall disruption and extraction efficiency, their high energy consumption and costs restrict the feasibility of large-scale applications [43].

2.2. Algal Chemical Processing Methods

Acid-base treatment serves as a commonly applied chemical pretreatment method for seaweed, enhancing energy utilization efficiency by decomposing cell walls and complex components. Acid treatment employs sulfuric or hydrochloric acid to convert polysaccharides into monosaccharides or oligosaccharides via acid hydrolysis, thereby promoting subsequent bioconversion [44]. Teh Y Y et al. significantly increased sugar recovery from red algae under conditions of 0.1–0.2 M sulfuric acid concentration, 150–170 °C, and 10 min heating, while simultaneously elevating biochar carbon content and reducing ash and moisture content. Optimizing acid concentration can further liberate sugars [39]. Laurens et al. found that acid-catalyzed pretreatment at low pH and moderate temperature significantly improved the conversion efficiency of carbohydrates to soluble sugars, with lipid extraction reaching 97% and glucose release rate exceeding 90%, markedly enhancing biofuel production [45].

Although acid treatment demonstrates marked efficacy in sugar extraction and fatty acid recovery, strong acid treatment is prone to generating byproducts while presenting risks of corrosiveness and environmental pollution [46]. Therefore, rational optimization of acid concentration and treatment conditions is required to balance efficiency with environmental impact.

Alkaline treatment typically employs alkali solutions such as sodium hydroxide or potassium hydroxide to disrupt cellulose and hemicellulose structures, enhancing seaweed digestibility and lipid extraction efficiency [47,48]. For example, Kang Zhang et al. demonstrated that alkaline thermal treatment significantly increased hydrogen production from brown macroalgae, yielding 69 mmol of high-purity hydrogen per gram with a 71% conversion rate. Additionally, hydroxides achieved in situ carbon dioxide capture during the reaction, while the Ni/ZrO₂ catalyst further promoted steam methane reforming and water-gas shift reactions, elevating hydrogen yield [16].

Compared to acid treatment, alkaline treatment exhibits lower environmental impact, with generated alkaline byproducts being readily recyclable [49]. Zhou et al. proposed the alkaline thermal treatment (ATT) method, converting high-moisture-content seaweed into high-purity hydrogen at 500 °C under atmospheric pressure, yielding nearly zero carbon

monoxide with only 0.3% carbon dioxide. The produced hydrogen can be directly utilized in fuel cells without additional purification [50].

However, alkaline treatment efficiency is considerably influenced by reaction time and temperature, typically requiring extended durations to achieve optimal results [51]. Consequently, practical applications demand species- and product-specific optimization of acid/alkaline treatment conditions to enhance conversion efficiency while minimizing byproduct generation.

While acid-base pretreatment remains ubiquitous in macroalgal biorefining, its intrinsic efficiency–environment compromise necessitates strategic mitigation. Convergent research must develop circular catalysts (e.g., recoverable heterogeneous acids, bio-derived bases) to enable cost-effective, low-waste processing [52]. These innovations will establish sustainable platforms for marine biomass valorization—specifically advancing hydrothermal liquefaction and anaerobic digestion pathways with $\leq 50\%$ carbon footprint reduction.

Solvent extraction and catalyst applications are increasingly prominent in algal chemical processing, demonstrating significant potential for enhancing lipid extraction and conversion efficiency [53,54]. Solvent extraction selectively isolates algal lipids using organic solvents such as ethanol, acetone, and hexane to boost biofuel yields [55]. Santoro et al. utilized an ethanol/cyclopentyl methyl ether blend that not only improved lipid extraction efficiency but also reduced environmental impact, rendering it suitable for biofuel production [56]. Choi et al. developed a CO₂-based switchable solvent system that modulates solvent polarity through CO₂ pressure adjustment, markedly increasing lipid extraction while exhibiting superior environmental benefits [57]. Anto et al. demonstrated that triamine solvents (e.g., dimethylbenzylamine, DMBA) achieve exceptional efficacy in lipid extraction from wet, high-salinity microalgae, offering enhanced sustainability over conventional solvents [58].

Supercritical fluid extraction (SFE) represents an advanced and environmentally benign alternative to traditional solvent-based techniques for the valorization of algal biomass. This method employs supercritical fluids, which possess tunable solvating power controlled by adjustments in temperature and pressure, enabling highly selective extraction of intracellular lipids. A key advantage of SFE is its favorable environmental footprint, as it typically utilizes non-toxic and recyclable solvents, thereby significantly reducing the generation of hazardous waste and volatile organic compounds. Studies have demonstrated that SFE can achieve efficient lipid recovery while maintaining the biochemical integrity of the extracts, which is crucial for subsequent biofuel conversion processes. However, the widespread adoption of this technology is currently hindered by substantial capital investment for high-pressure infrastructure and the need for meticulous process optimization. Future research should prioritize the development of cost-effective systems and the exploration of integrated biorefinery approaches to enhance the scalability and economic feasibility of SFE for algal bioenergy applications [59].

Solvent selection critically governs lipid extraction efficacy due to inherent polarity and solubility variations, necessitating optimized solvent systems—either singular or binary/ternary blends—for maximal yield [60]. However, solvent extraction is costly and prone to generating volatile organic compounds (VOCs). Therefore, in industrial applications, the recovery and treatment of solvents must be given due attention to reduce environmental impact.

Catalyst applications enhance the degradation rates of algal components and boost energy conversion efficiency by accelerating chemical reactions. Acidic catalysts, such as phosphoric acid and sulfuric acid, facilitate polysaccharide hydrolysis and are particularly suitable for bioethanol production [61]. For instance, Yang et al. employed mixed-acid catalysis (sulfuric and acetic acids) during hydrothermal liquefaction (HTL) of undried

seaweed at 290 °C for 20 min with a 1:3 biomass-to-water ratio, achieving significant improvements in bio-oil yield and quality [62].

Alkaline catalysts enable efficient transesterification of algal lipids into biodiesel [63]. Chamola et al. demonstrated that sodium hydroxide (NaOH) catalysis under optimized conditions—methanol-to-dry-algae mass ratio 8:1, catalyst loading 3.499 wt%, 50 °C, and reaction time 73.637 min—achieved 87.421% biodiesel yield [64]. This precision-tuned protocol highlights NaOH's effectiveness for industrial-scale biodiesel synthesis from algal feedstocks.

In recent years, the application of novel catalysts in algal processing has gradually gained prominence, exhibiting exceptional advantages in efficiency and low byproduct generation. For instance, Delmiro et al. employed an HZSM-5 catalyst for catalytic flash pyrolysis of lipids at 500 °C, substantially enhancing the yield of renewable aromatic hydrocarbons and demonstrating significant potential for sustainable biofuel production [65]. Concurrently, Norouzi et al. investigated the performance of a cobalt-molybdenum-loaded HZSM-5 and mesoporous silicon composite catalyst (ZH), revealing its capacity to markedly reduce the concentration of acetic and formic acids in bio-oil—from 9.56 wt% to 8.12 wt%—while simultaneously decreasing phenolic and furfural content, thereby improving fuel quality [66].

Moreover, Santillan-Jimenez et al. demonstrated the transformation of algal oil into diesel-like hydrocarbons using a sequential approach: lipid impurities were first removed via low-cost adsorbents (e.g., activated carbon), followed by deoxygenation reactions catalyzed by a nickel-aluminum layered double hydroxide catalyst at 260 °C. This process significantly improved fuel yield while mitigating environmental impact [67].

Chemical treatments, such as acid/base treatment and solvent extraction, have been widely deployed to deconstruct the complex constituents of macroalgae, thereby enhancing the conversion efficiency for fuels and biomaterials [68]. In particular, chemical approaches present distinct advantages in boosting conversion efficiency and reaction selectivity due to their adjustable operating parameters and continuous catalyst optimization [69]. Conversely, challenges including high operational costs, environmental contamination, and byproduct disposal and management remain critical issues requiring resolution. Presently, chemical processing is deemed one of the most promising approaches for algal energy utilization and is well-suited as a core methodology for biofuel and chemical production.

2.3. Algal Bioprocessing Methods

Enzymatic hydrolysis and fermentation serve as fundamental biological approaches for macroalgae processing, facilitating the breakdown of intricate biomacromolecules into conversion-ready monomers to optimize energy recovery efficiency [13]. Specifically, enzymatic hydrolysis employs target-specific enzymes (e.g., cellulases and proteases) to depolymerize cellulose, hemicellulose, and proteins, thereby releasing fermentable sugars and amino acids to support downstream biotransformation [70]. Notably, Ge et al. revealed that dilute sulfuric acid pretreatment significantly enhanced enzymatic hydrolysis efficiency for algal waste substrates (e.g., *Laminaria residues*), with glucose yields exhibiting linear correlation to pretreatment intensity—demonstrating scalable biomass valorization potential [71].

In lipid extraction studies involving microalgae, Lee et al. noted that enzymatic hydrolysis effectively liberates lipids via degradation of cell walls or membranes [72]. Extending this research, Wu et al. demonstrated that alkaline pretreatment coupled with enzymatic hydrolysis—employing a combination of cellulases, proteases, lysozymes, and pectinases—significantly elevated lipid extraction yields, with the multi-enzyme system outperforming single-enzyme applications [73]. Concurrently, Demuez et al. investigated

the deployment of microalgae-lysing microorganisms secreting enzymatically active substances for microalgal cell disruption, revealing that this approach reduced enzymatic costs while enhancing rupture efficiency [74]. In parallel, Tan et al. examined solid acid catalyst-assisted pretreatment of macrophyton cellulose residues (e.g., *Saccharina* spp.), followed by enzymatic hydrolysis for bioethanol production; under optimized pretreatment conditions, enzymatic hydrolysis substantially increased fermentable sugar yields, establishing a robust foundation for bioethanol synthesis [75]. Critically, these collective studies confirm that enzymatic hydrolysis not only boosts the extraction efficiencies of sugars and lipids but also reduces energy consumption and processing time in subsequent fermentation stages.

Beyond the application of individual enzymes, the integration of multi-enzyme systems represents a significant advancement for the cascading conversion of raw seaweed materials. These systems are designed to operate synergistically within a one-pot configuration, where a combination of carbohydrate, proteases, and lipases sequentially deconstructs the complex polymeric network of algal biomass into fermentable sugars, amino acids, and lipids. This integrated approach streamlines the bioconversion process by minimizing intermediate separation steps, thereby reducing processing time and potential inhibitory effects. This cascading action not only improves substrate conversion efficiency but also paves the way for more economical and sustainable biorefinery models by consolidating unit operations [59].

Enzymatic hydrolysis demonstrates superior conversion efficiency and reduced environmental implications when compared with mechanical and chemical treatment methodologies [76]. Nevertheless, the elevated cost of enzymes remains the primary constraint impeding their large-scale industrial implementation.

Fermentation converts organic matter within algae into biofuels or valuable chemicals via microbial metabolism [77], operating through two predominant pathways: anaerobic fermentation for producing gaseous fuels such as biogas [78], and aerobic fermentation for generating liquid fuels like bioethanol [79]. Specifically, Ding et al. developed an integrated two-stage process coupling dark fermentation with anaerobic digestion to co-produce biohydrogen and biomethane. In the dark fermentation phase, biohydrogen yields reached 57.4 mL/gVS—representing a 60.8% increase over control samples. Subsequently, the residual substrate was transferred to anaerobic digestion for biomethane generation. This synergistic methodology substantially enhanced the co-production efficiency of hydrogen and methane [80].

Moreover, Ye Lee et al. investigated the influence of extremely weak acid pretreatment on ethanol production from brown algal extracts, a method that substantially diminishes acid-induced degradation of algal biomass while enhancing substrate fermentability [81]. During subsequent saccharification and fermentation stages, process optimization achieved high-efficiency conversion of liberated sugars to ethanol, with conventional microorganisms such as yeast and lactic acid bacteria demonstrating critical catalytic functionality throughout the fermentation process.

Notwithstanding the maturity of fermentation technologies, their application to algal feedstocks encounters persistent challenges, including feedstock compositional heterogeneity constraining fermentation efficiency and inadequate scalability for industrial deployment [82,83]. Consequently, future research warrants strategic refinement of integrated enzymatic hydrolysis-fermentation processing to achieve cost-effective valorization of algal biomass for bioenergy production.

Biological treatment leverages microbial and enzymatic activities to decompose the complex organic constituents of macroalgae into readily utilizable energy substrates—such as monosaccharides and amino acids—proving particularly apt for producing high-value-

added biofuels [84]. Nevertheless, this approach faces intrinsic constraints: restricted enzymatic/microbial specificity, heightened sensitivity to temperature and pH fluctuations, and substantial operational costs, thereby impeding feasibility for large-scale industrial implementation. Consequently, biological processing demonstrates greater suitability for high-value chemical extraction and discrete, specialized fuel production under controlled conditions.

In summary, distinct advantages are exhibited across physical, chemical, and biological treatment modalities. Physical treatment serves as a strategic pretreatment approach, reducing biomass transport and processing expenses. Biological processing demonstrates unique efficacy for high-value product synthesis, while chemical treatment stands out through its superior energy conversion efficiency and operational flexibility—particularly given recent progress in catalytic systems and process optimization, rendering it optimally suited for scaled industrial implementation. Consequently, future research should prioritize innovative refinements in chemical processing, synergistically integrated with complementary methods to maximize overall energy utilization efficiency. A consolidated evaluation of mainstream seaweed treatments is presented in Tables 1 and 2, highlighting their conversion advantages and intrinsic limitations.

Table 1. Some common seaweed treatments.

Seaweed Type	Polysaccharides	Monosaccharides /Monosaccharide Derivatives	Disadvantages
Pyrolysis	Medium-low temperature rapid pyrolysis	Rapid conversion of macroalgae to bio-oil, gaseous fuels, and char products; high energy density with demonstrated industrialization potential Mature technology enabling organic wastewater treatment with biogas co-generation (biomethane); low-cost and eco-friendly operations High-efficiency monosaccharide extraction for bioethanol synthesis; superior bioconversion rates; minimal environmental pollution	High energy consumption; requires post-treatment refining of bio-oil to improve fuel quality
Anaerobic Fermentation	Sugar-to-bioethanol fermentation		Slow kinetics; inefficient decomposition of low-carbohydrate substrates; high sensitivity to environmental conditions
Enzymatic Hydrolysis	Enzymatic pretreatment/cellulase hydrolysis		Prohibitive enzyme costs; necessity for activity-enhancing additives; limited substrate versatility
Bioelectrochemical	Microbial fuel cells /electrochemical hydrolysis	Concurrent organic matter degradation and electricity generation; viability for small-scale research and integrated energy systems	Low technological readiness; suboptimal electricity conversion efficiency; microbial consortia instability under environmental perturbations
Liquefaction	High-temperature/pressure liquefaction	High-yield liquid bio-oil production with elevated energy density; direct applicability as drop-in fuel	Demanding high-pressure apparatus; operational harshness; complex product profiles requiring energy-intensive purification
Hydrothermal Carbonization	Subcritical hydrothermal carbonization	Moderate operational temperatures yielding stable biochar; reduced reactor corrosion risks	Lower conversion efficiency than pyrolysis; extended reaction durations needed for optimal output

Table 2. Analysis of the prospects of some common seaweed treatment methods.

Seaweed Type	Efficiency	Cost	Sustainability
Pyrolysis	High energy density bio-oil yield	High (energy-intensive process, catalyst cost)	Medium (handles diverse feedstock, but requires product upgrading)
Anaerobic Fermentation	Medium (slow kinetics, substrate-dependent)	Low (mature, low-operational cost technology)	High (waste reduction, biogas production)
Enzymatic Hydrolysis	High bioconversion rate for target sugars	High (cost of specific enzymes, additives)	High (mild conditions, minimal pollution)
Bioelectrochemical	Low (current technology readiness level)	Very High (complex system, expensive materials)	High (direct energy recovery from organics)
Liquefaction	High yield of liquid product	High (high-pressure/temperature reactor cost)	Medium (utilizes wet biomass, but harsh conditions)
Hydrothermal Carbonization	Medium (lower conversion efficiency than pyrolysis)	Medium (moderate conditions, but extended durations)	High (converts wet feedstock, produces stable biochar)

3. Algal Biomass Upgrading Technologies for Enhanced Bioenergy Conversion

Figure 2 demonstrates the three major product pathways—solid, liquid, and gas—which underlie the upgrading strategies examined in this section.

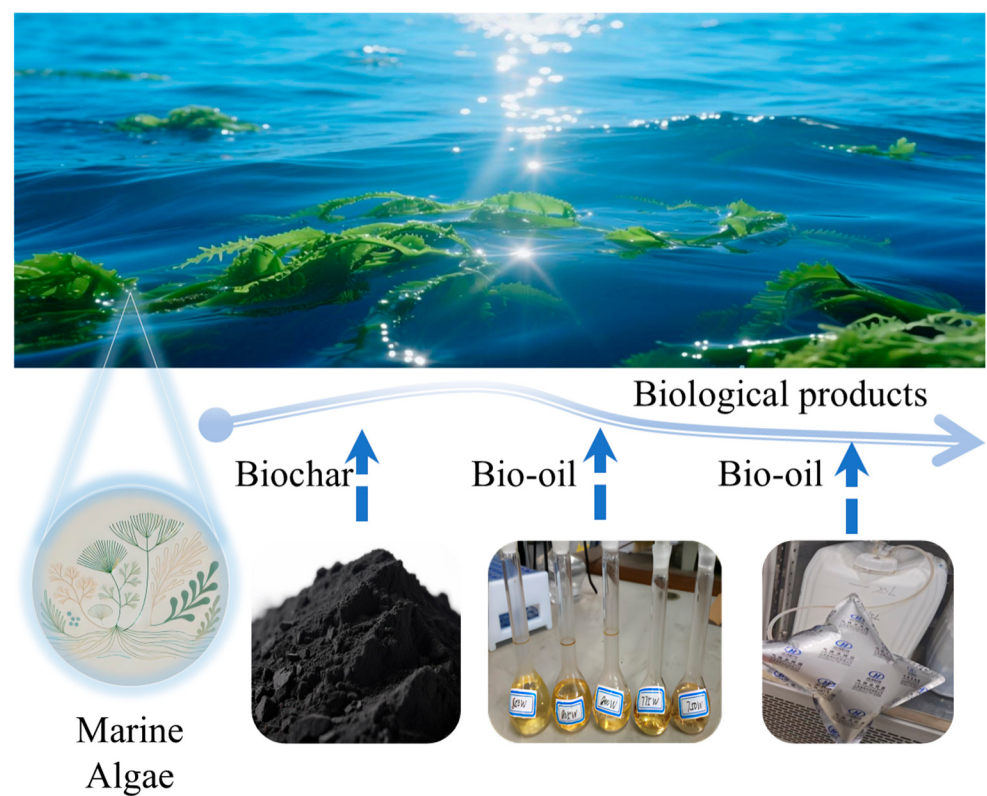


Figure 2. Three product pathways for the energy utilization of seaweeds.

3.1. Advanced Valorization Pathways for Solid-Phase Products

Solid-phase products primarily include biochar and fuel pellets, with the former produced through the thermal decomposition of macroalgae. Biochar manifests as an inert, carbon-rich material suitable for energy generation while concurrently serving critical environmental roles in soil amendment, water retention, and contaminant adsorption [85]. Research by Dang et al. demonstrates that processing algal waste via integrated composting

and biochar production not only enhances soil quality but also significantly boosts microbial activity and fertility. Crucially, biochar synthesis functions as a carbon sequestration mechanism, substantially mitigating greenhouse gas emissions. Variable effectiveness of distinct macroalgal species during composting—experimentally validated—further corroborates their potential in sustainable biochar fabrication [86].

Fuel pellets produced by mechanical briquetting of large algae are an environmentally friendly energy alternative [87]. As documented by Skoglund et al., varying macroalgal species exhibit distinct combustion energetics and thermal behaviors; targeted tailoring of these properties enhances combustion efficiency while reducing hazardous emissions. Furthermore, co-combustion with complementary fuels offers potential for optimized thermal release profiles [88].

Additionally, algal-derived biochar finds extensive application owing to its distinctive chemical properties. Tan et al. emphasized the inherent advantages of algae as a biochar feedstock, noting high yield potential, enhanced safety, and favorable economic viability. Crucially, thermal decomposition of algal biomass generates graphitic-N structures and N-O surface functionalities, which activate free-radical pathways and amplify electron transfer capacity within porous matrices—thereby substantially augmenting catalytic performance. Within wastewater remediation contexts, nitrogen-doped algal biochar exhibits exceptional pollutant degradation efficiency and sorption capacity [89]. Substantiating this, Liu et al. investigated *Ulva*- and chlorophyte-derived activated carbons for gaseous mercury removal, revealing that marine algal activated carbon significantly surpasses conventional pyrolytic carbons in Hg^0 adsorption performance, thus establishing an innovative contaminant mitigation strategy [90].

Collectively, macroalgal biochar synthesized through chemical or pyrolytic methodologies demonstrates remarkable carbon sequestration capacity and robust adsorption performance, rendering it highly suitable for applications in soil remediation, contaminant abatement, and terrestrial carbon sink enhancement. However, its comparatively lower energy density precludes its viability as a primary energy feedstock.

3.2. Advanced Value-Added Approaches for Liquid-Phase Products

Liquid-phase derivatives primarily encompass bio-oils and water-soluble nutrients [91], with the former resulting from chemical transformation (e.g., hydrolysis or enzymatic hydrolysis) of algal organic matter into liquid fuels. Bio-oils exhibit a hydrocarbon profile analogous to conventional petroleum, functioning as viable diesel substitutes while possessing versatility for further upgrading into industrial lubricants and polymer feedstocks [92].

Hydrothermal liquefaction represents one of the core technologies for aqueous phase valorization of macroalgae, directly converting algal biomass into liquid fuels under elevated temperature and pressure conditions [93]. This method does not require pre-drying treatment, rendering it particularly suitable for macroalgal resources with high moisture content. Research by Anastasakis demonstrated that hydrothermal liquefaction, under optimized conditions of temperature, pressure, and reaction time, significantly enhances the yield of liquid products while simultaneously modulating the relative proportions of organic components such as fatty acids and alcohols. At higher temperatures and pressures, the quality and composition of the liquid products are optimized, offering a promising approach for liquid fuel production [94].

An investigation into catalyst-free *in situ* transesterification technology under subcritical conditions was conducted on wet-state microalgae for direct conversion into fatty acid methyl esters (FAME). This approach eliminates the need for dehydration and extraction steps. Optimized parameters comprised a reaction temperature of 220 °C, duration of 2 h, and a solvent-to-solid ratio of 8 mL/g with an 80% moisture content, achieving a FAME

yield of 74.6%. Compared with conventional transesterification techniques, this method demonstrates reduced energy consumption and lower environmental impact, thereby establishing a viable alternative for biodiesel production [95].

El-Hefnawy et al. investigated an integrated approach involving co-pyrolysis of macroalgal residue with microalgae to produce liquid biofuels, demonstrating that co-pyrolysis significantly enhanced bio-oil production while enabling efficient utilization of algal waste. This integrated technique delivers dual advantages of bio-oil recovery and waste valorization [96]. Additionally, El-Hefnawy's team examined an integrated system combining solid-state pre-fermentation with hydrothermal liquefaction (HTL). By leveraging endogenously produced bio-ethanol during solid-state fermentation, the pretreatment of algal biomass was optimized, subsequently increasing crude bio-oil yields substantially. The study compared HTL outcomes using three feedstocks: raw unfermented biomass, post-fermentation residues (after ethanol separation), and ethanol-containing fermentation broth. Results confirmed that the fermentation broth retaining ethanol achieved the highest bio-oil production rate, thereby offering a more efficient and sustainable solution for biofuel production [97].

Further research indicates that optimizing liquefaction temperature and pressure is critical for enhancing both bio-oil yield and quality [93]. However, the operational requirements of high temperature and pressure incur substantial energy consumption and elevated equipment costs. At present, although liquefaction technologies have achieved promising results in laboratory-scale studies, industrial-scale implementation remains challenging due to excessive energy demands and stringent process conditions.

Collectively, the bio-oil generated through liquefaction technologies offers an efficient pathway for energy recovery from algal biomass. Particularly under optimized hydrothermal liquefaction (HTL) and in situ transesterification processes, this approach not only significantly enhances production yield but also reduces energy consumption and minimizes environmental impacts, thereby laying a substantive foundation for sustainable biofuel production.

Liquid bio-oil, as one of the primary products derived from algal energy conversion, demonstrates significant potential for substituting conventional fuels such as diesel. Consequently, upgrading techniques for liquid-phase products within chemical processing systems are particularly critical. Currently, several prevalent upgrading approaches include the following:

Hydrodeoxygenation (HDO): Bio-oil contains a significant amount of oxygenated functional groups, resulting in low calorific value and high corrosiveness. The HDO process utilizes catalysts (e.g., Ni-based, Mo-based catalysts) under elevated temperatures and pressures (300–450 °C, 5–15 MPa) to reduce oxygen content in bio-oil through hydrogenation reactions, thereby significantly enhancing heating value and combustion stability [98]. This modification brings its properties closer to diesel-like hydrocarbon standards. Research by Soni et al. demonstrated that nickel–cobalt (Ni/Co) catalysts supported on natural clay efficiently convert microalgal oil into diesel-grade hydrocarbons. Furthermore, it was demonstrated that HDO exhibits superior carbon atom economy and energy utilization efficiency compared to decarboxylation and decarbonylation reactions, while remarkably reducing CO₂ emissions. The total yield of saturated hydrocarbons reached 84–86 wt%, with nearly consistent deoxygenation rates observed across fatty acids of varying chain lengths [99].

Plasma-assisted hydrodeoxygenation (HDO) technology investigated by Mudassir et al. significantly enhances the deoxygenation efficiency of bio-oil under low-temperature conditions through the generation of excited-state species. Compared to conventional HDO methods, this approach demonstrates superior conversion efficiency while simultane-

ously reducing reaction temperatures and energy consumption, thereby providing a novel pathway for bio-oil upgrading [100].

Although hydrodeoxygenation (HDO) technology can significantly enhance bio-oil quality, its requirement for elevated temperatures and associated catalyst costs present major obstacles for industrial-scale implementation. Consequently, future research must focus on catalyst performance optimization and process cost reduction to achieve economic viability [101].

The catalytic cracking process constitutes an upgrading technology whereby long-chain macromolecules within bio-oil are cracked under elevated temperatures using catalysts, such as ZSM-5 and HZSM-5, thereby converting them into low-molecular-weight hydrocarbons and aromatic compounds [102]. This method not only reduces the oxygen content of bio-oil but also optimizes its carbon chain structural configuration, aligning it more closely with fuel quality specifications. Catalytic cracking demonstrates favorable reaction selectivity and processing efficiency, rendering it applicable to large-scale bio-oil upgrading operations.

Galadima investigated the synergistic effects of combining hydrothermal liquefaction with catalytic cracking for bio-oil upgrading. Studies demonstrate that heterogeneous catalysts significantly enhance reaction selectivity and process efficiency during liquefaction, thereby improving the chemical stability and physical properties of bio-oil. Comparative analyses of multiple catalysts reveal that both catalyst type and reaction conditions exert substantial influence on liquid fuel quality [103]. Hu et al. examined the impact of microporous ZSM-5 and mesoporous MCM-41 catalysts during catalytic hydropyrolysis on bio-oil yield and quality. Results indicate that ZSM-5 increased bio-oil yield from 36.22% to 51.48%, while MCM-41 elevated it to 41.84%. Both catalysts promoted higher aromatic hydrocarbon content while reducing small-molecule acids, concurrently suppressing the formation of furans and ketones, thereby markedly improving bio-oil stability [104].

Fang et al. employed a deep eutectic solvent (DES) synthesized from lactic acid and choline chloride for biomass pretreatment, integrated with ZSM-5 catalyzed fast pyrolysis, significantly enhancing bio-oil quality. DES pretreatment effectively reduced lignin and carboxyl group content while increasing the C/O ratio and crystallinity. Under optimized pyrolysis conditions, bio-oil yield reached 54.53%, with aromatic hydrocarbons accounting for 39.99% of the product [105]. Zhang et al. further explored a novel approach combining UV/H₂O₂ advanced oxidation pretreatment with ZSM-5 catalyzed fast pyrolysis to upgrade bio-oil properties. UV/H₂O₂ pretreatment efficiently removed oxidative compounds, optimized cellulose content, and reduced acidic and phenolic substances through delignification. When coupled with ZSM-5 catalysis, hydrocarbon and monocyclic aromatic hydrocarbon production were significantly promoted. Response surface methodology was utilized to optimize H₂O₂ concentration and pretreatment duration, establishing their influence on key chemical constituents [106].

Overall, catalytic cracking offers an efficient solution for bio-oil upgrading through the optimization of catalyst performance and reaction conditions. When combined with deep eutectic solvent pretreatment or UV/H₂O₂ oxidation technology, this approach further enhances bio-oil yield and quality, presenting a new research perspective for the value-added utilization of algal biomass. However, the expensive investment and maintenance in its production process still limit the application of the catalyst in the conversion of algae into biofuels. Its operating costs and raw material costs remain high. Although integrating the production chain can reduce some costs, more complex processing plans will still generate negative profits [59].

A current frontier in the hydrodeoxygenation (HDO) research of bio-oil involves structural optimization of catalysts to address deactivation caused by coking during

reactions [107]. Coking phenomena significantly impair catalyst activity and lifespan, thereby constraining the upgrading efficiency of bio-oil [108]. Consequently, researchers have developed porous-structured catalysts and enhanced their anti-coking properties through surface functionalization [109,110]. Notably, bifunctional catalysts and nanostructured catalysts demonstrate superior coking resistance while improving deoxygenation efficiency, thereby extending catalyst longevity [111].

The introduction of rare earth metals and alkali metal promoters has also been demonstrated to effectively enhance the stability and anti-coking performance of catalysts [112]. Future research should prioritize the development of durable and low-cost catalyst materials while further improving the efficiency of hydrodeoxygenation (HDO) reactions through optimization of microstructure and surface properties. Concurrently, the regeneration and recycling technologies of catalysts represent critical factors in enhancing process economics. Looking ahead, an important development trajectory in this field involves combining high-performance catalysts with other upgrading technologies—such as catalytic cracking or hydrothermal liquefaction—to drive scalable applications of algal bioenergy utilization through integrated innovation.

3.3. Advanced Value-Added Methods for Gas-Phase Products

The gaseous products primarily consist of biogas and hydrogen, which are generated through the anaerobic fermentation or thermochemical gasification of macroalgal organic matter, converting it into combustible gases [113]. Biogas, predominantly composed of methane (CH_4), exhibits a high calorific value suitable for electricity generation or heating applications. Critically, its carbon emissions are significantly lower compared to conventional fossil fuels. Hydrogen serves as a pivotal vector for future clean energy, finding extensive applications in fuel cells and as a chemical feedstock. Macroalgae gasification technology demonstrates potential for reducing energy consumption while enhancing hydrogen production rates, thereby offering a promising route for advancing clean energy development.

In the field of biogas production, Thakur et al. investigated the biodegradability of various seaweed species and their methane yield, significantly enhancing production efficiency through optimized fermentation conditions [114]. Lin R et al. explored the impact of hydrothermal pretreatment on gaseous biofuel production from macroalgae. The study revealed that hydrothermal pretreatment (100–180 °C) enhanced the solubility of seaweed, with soluble chemical oxygen demand (sCOD) exceeding that of untreated samples by 207.5%. Under 140 °C pretreatment, dark fermentative biohydrogen production from seaweed increased marginally, while biomethane yield rose from 281.4 mL/gVS to 345.1 mL/gVS, achieving sCOD removal efficiency of 86.1% [11]. The study demonstrates the profound implications of hydrothermal pretreatment on algal structural integrity and biochemical composition, effectively enhancing biogas productivity.

Tabassum et al. evaluated the viability of seaweed as a feedstock for renewable gaseous fuels in Ireland, highlighting that seaweed offers advantages including high growth rates, substantial productivity, robust CO_2 fixation capacity, and independence from arable land or freshwater resources, positioning it as a feasible pathway for reducing dependence on fossil fuels. Studies have also demonstrated that the biochemical composition of seaweed, which is influenced by species, growth environment, cultivation methods, and harvest timing, directly determines its biomethane production yield [115]. Concurrently, Tabassum et al. investigated methane yield variations across different anatomical components of brown algae (e.g., stipes, holdfasts, blades), determining that stipes exhibit the highest methane productivity and that seasonal fluctuations substantially impact production yields.

This research further substantiates the potential utility of brown algae as a viable substrate for bioenergy feedstocks [116].

In the context of hydrogen production, Czyrnek-Del tre et al. conducted a lifecycle assessment of seaweed-derived biomethane focusing on temperate Integrated Multitrophic Aquaculture (IMTA) systems. Their findings demonstrate that the lifecycle greenhouse gas emissions for seaweed biomethane are reduced by approximately 70–80% compared to conventional fossil fuels, highlighting its significant environmental advantages [117].

Overall, the production of gaseous products has demonstrated significant economic and environmental advantages through technological optimizations—such as hydrothermal pretreatment and co-digestion models—in conjunction with life cycle assessment, thereby providing a sustainable solution for the energy valorization of algae.

4. Economic Assessment of Algal Biofuels

Life cycle assessment (LCA) studies provide critical insights into the environmental performance of algal biofuel and co-product systems, revealing distinct advantages and challenges when compared to conventional fossil-based systems. These systems generally demonstrate lower CO₂ emissions relative to their fossil counterparts, particularly when configured to produce biodiesel alongside protein or succinate, though they often involve higher fossil energy consumption primarily due to energy-intensive processes such as cultivation and harvesting. A significant benefit of algal systems is their considerably lower land requirement, and their environmental profile can be further improved through strategies like nutrient uptake from wastewater, which reduces eutrophication impacts, and internal resource recirculation, which diminishes the demand for external inputs. However, conducting LCAs for these multi-functional systems presents methodological challenges, especially in accounting for co-products, carbon capture, and recycling loops; the application of substitution methods can avoid greenhouse gas emissions, but the outcomes are sensitive to modeling choices and algal composition. From a technological perspective, chemical conversion routes (e.g., for biodiesel) typically offer higher efficiency for liquid biofuels, whereas biological pathways (e.g., for biomethane) often yield a lower carbon footprint for gaseous fuels. Emerging hybrid approaches, such as combining thermochemical liquefaction with biological digestion, show promise for synergizing these advantages, potentially enhancing overall sustainability and resource efficiency. Future research should prioritize generating robust, comparative LCA data to validate these synergies, improve the transparency of modeling assumptions—particularly regarding carbon storage duration and co-product allocation—and guide the scale-up of the most sustainable integrated biorefinery models [59,118].

Future research should focus on the integrated optimization of multiple treatment methods to achieve efficient and low-cost conversion of algal biomass for energy purposes. The development of low-cost and highly durable catalyst materials, coupled with the enhancement of catalyst regeneration and recycling technologies, will be pivotal in reducing the costs associated with bio-oil upgrading. Concurrently, assessing the feasibility of large-scale liquid bio-oil production from both technical and economic perspectives is essential to advance the broader application of algal biomass in the energy and chemical industries. An analysis of Technology Readiness Levels (TRL) reveals significant variation across conversion pathways: anaerobic digestion for biogas production has reached TRL 8–9 with multiple commercial-scale plants operational worldwide, particularly in Europe and Asia, utilizing seaweed co-digestion with other organic wastes. In contrast, thermochemical routes such as hydrothermal liquefaction and catalytic pyrolysis for liquid bio-oil production remain predominantly at TRL 4–6 [119,120], with limited commercial implementation due to challenges in catalyst durability and process economics. Biological

routes for bioethanol and higher-value chemicals typically operate at TRL 4–5, constrained by scalability and enzymatic costs. This underscores the need for further techno-economic optimization and policy support to bridge the gap between pilot demonstrations and full-scale deployment. Through integrated innovation, algal-based energy utilization is poised to become a vital component of sustainable energy systems, offering a tangible solution to mitigate the energy crisis and environmental issues.

5. Conclusions and Prospects

This paper systematically reviews three primary treatment approaches (physical, chemical, and biological) for the energetic utilization of seaweed and their application potential across solid, liquid, and gaseous energy products. As a fundamental pretreatment method, physical treatment significantly enhances the energy density and combustion properties of seaweed; however, its conversion efficiency and product quality remain suboptimal. Biological treatment, employing enzymatic hydrolysis and fermentation technologies, converts complex seaweed components into high-value-added biofuels, but such methods face challenges for large-scale industrialization due to high costs and relatively low efficiency. Under current technological conditions, chemical treatment approaches exhibit the highest energy conversion efficiency and strong flexibility, rendering them particularly applicable to the production of liquid bio-oil.

This study focuses on various upgrading methods for liquid bio-oil, including hydrodeoxygenation, catalytic cracking, and transesterification. These technologies significantly enhance the fuel quality and stability of bio-oil. Among them, hydrodeoxygenation and catalytic cracking have garnered extensive attention due to their advantages in removing oxygen-containing functional groups and optimizing carbon chains. Current research has progressively introduced novel catalysts that enhance reaction efficiency and product quality by optimizing microstructures and improving coke resistance, thereby establishing a technical foundation for the industrial application of bio-oil. Furthermore, solid products such as biochar demonstrate significant application value in carbon sequestration, soil amendment, and pollutant adsorption, while gaseous outputs, including biogas and hydrogen, provide promising routes for clean energy development.

Despite the promising advances in algal bioenergy conversion, several critical research gaps must be addressed to achieve economic competitiveness. Key gaps include the development of low-cost, durable, and recyclable catalysts for hydrodeoxygenation and catalytic cracking to reduce upgrading expenses; the optimization of integrated process economics through techno-economic assessments that compare chemical, biological, and hybrid routes under realistic scale-up conditions; the mitigation of energy-intensive pre-treatment steps such as drying and milling via renewable energy integration or novel low-moisture tolerance technologies; the enhancement of synergies in hybrid systems like hydrothermal liquefaction coupled with catalytic upgrading to improve overall efficiency and yield; and the comprehensive evaluation of environmental impacts through life cycle assessment to ensure sustainability alongside cost-effectiveness. Addressing these gaps will require interdisciplinary efforts to bridge laboratory-scale innovations with industrial implementation, ultimately enabling algal biofuels to compete with conventional fossil fuels.

Future research should focus on the integrated optimization of multiple treatment methods to achieve efficient and low-cost conversion of algal biomass for energy purposes. The development of low-cost and highly durable catalyst materials, coupled with the enhancement of catalyst regeneration and recycling technologies, will be pivotal in reducing the costs associated with bio-oil upgrading. Concurrently, assessing the feasibility of large-scale liquid bio-oil production from both technical and economic perspectives is essential to advance the broader application of algal biomass in the energy and chemical industries.

Through integrated innovation, algal-based energy utilization is poised to become a vital component of sustainable energy systems, offering a tangible solution to mitigate the energy crisis and environmental issues.

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