

Review paper

Marine Microalgae as a Biorefinery Platform: Cultivation, Lipid Extraction, and Bioenergy Conversion

Muhammad Zain Imran^{1, *}¹ Department of Marine Science, Faculty of Science and Technology, UIN Sunan Ampel Surabaya, Jl. Ahmad Yani No. 117, Surabaya 60237, East Java, Indonesia.* Corresponding author: imranzain856@gmail.com

Abstract: Marine microalgae are being investigated as feedstocks for biofuel and bioproduct production because many marine taxa can accumulate lipids while being cultivated in seawater or saline media, reducing dependence on freshwater resources. However, the economic and environmental performance of marine microalgal biorefineries depends strongly on biomass productivity, lipid content, cultivation conditions, harvesting requirements, downstream energy demand, and co-product recovery. Although recent studies have examined cultivation, lipid recovery, and fuel conversion, they often discuss these advances separately, making it difficult to assess the marine microalgal biorefinery as an integrated system. This review examines peer-reviewed studies published between 2020 and 2025 that cover the full production pathway, from species selection and cultivation to lipid extraction, bioenergy conversion, and sustainability assessment. The review focuses on marine genera such as *Nannochloropsis*, *Tetraselmis*, and *Phaeodactylum tricornutum*, as well as cultivation strategies including open ponds, photobioreactors, hybrid systems, low-cost media, and two-phase protocols that enhance lipid accumulation under abiotic stress while maintaining satisfactory biomass productivity. The review also compares open raceway ponds and closed photobioreactors, summarizes recent developments in harvesting and lipid extraction technologies, and evaluates findings from techno-economic analyses and life-cycle assessments. Across the published literature, harvesting, dewatering, and downstream processing are major contributors to energy consumption and production costs, limiting large-scale commercialization. By integrating evidence from upstream cultivation and downstream processing, this review identifies current knowledge gaps and highlights research priorities that could improve the technical, economic, and environmental performance of marine microalgal biofuel production.

Keywords: Marine microalgae, Biorefinery, Biofuels, Lipid extraction, Techno-economic analysis

1. Introduction

Depleting fossil fuel reserves and tightening climate regulations drive the search for liquid biofuels that can replace petroleum in heavy transport and aviation [1, 2]. First-generation bioethanol and biodiesel from food crops like corn, sugarcane, soybean, and palm proved commercially viable, but their use of prime farmland and freshwater raised long-term food security concerns [3, 4]. Second-generation lignocellulosic biomass can reduce direct competition for arable land, yet processing recalcitrant plant cell walls requires harsh chemical pretreatments that remain too expensive for wide adoption [5]. Microalgal feedstocks offer an alternative route. They feature high solar conversion efficiency, short doubling times, and rapid carbon fixation per unit area [6, 7].

Microalgal biomass is a versatile third-generation feedstock that can produce drop-in liquid biofuels and sustainable energy precursors [8–10]. Beyond liquid fuels, microalgal feedstocks also serve as sustainable platforms for valuable bioproducts across the food, feed, and materials sectors [11, 12]. Marine species can offer practical advantages over freshwater strains because they can be cultivated in seawater or brackish media, potentially reducing dependence on freshwater resources [13, 14]. Prominent marine genera, including *Nannochloropsis*, *Tetraselmis*, and the diatom *Phaeodactylum tricornutum*, naturally synthesize high levels of neutral lipids, mainly triacylglycerols (TAGs). These lipids serve as chemical precursors for hydrotreated renewable diesel, fatty acid methyl esters, and sustainable aviation fuel [15–17].

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Many of these organisms also produce marketable secondary compounds, such as omega-3 polyunsaturated fatty acids, carotenoids, and proteins [18, 19].

Despite these advantages, scaling marine microalgae to an industrial energy platform presents technical hurdles across every stage of production [8, 20]. Microalgae commonly exhibit a physiological trade-off in which conditions that promote lipid accumulation can reduce cellular growth rates [21, 22]. Limiting nitrogen or phosphorus redirects metabolic pathways toward TAG storage, but reduced growth rates lower overall volumetric biomass yields [23–25]. Researchers address this trade-off by overexpressing lipogenic genes, such as type-2 diacylglycerol acyltransferase (DGAT2) in *P. tricornutum*, to boost TAG synthesis without halting growth [26–28]. Others apply adaptive laboratory evolution or mutagenesis to select strains resilient to salinity and temperature shifts [29, 30]. Additional approaches include introducing bacterial signaling molecules or phytohormones to stimulate diatom growth and lipid storage simultaneously [31, 32]. System designers must also choose between open raceway ponds with low capital costs and closed photobioreactors that offer tighter process control, higher cell densities, and better contamination defense [33, 34].

Harvesting, dewatering, and lipid extraction represent major economic barriers [35, 36]. Marine cultures are dilute, usually containing 0.2 to 3 grams of dry biomass per liter of seawater. Processing thousands of liters of water per kilogram of algae via centrifugation or filtration requires significant electricity, increasing operating costs [36, 37]. Once dewatered, breaking cell walls, such as the complex polysaccharide structures in *Tetraselmis*, requires mechanical shear or enzymatic disruption [38, 39]. Traditional lipid extraction relies on organic solvent mixtures like chloroform and methanol, which carry environmental and safety risks. Process engineering has therefore shifted toward green solvents, supercritical fluid extraction, and hydrothermal liquefaction pathways that process wet biomass directly without prior drying [39–41].

Techno-economic analyses and life-cycle assessments demonstrate that standalone, single-product biofuel facilities operating under current energy market conditions yield negative net energy returns and uncompetitive minimum fuel selling prices [42, 43]. To achieve economic viability, modern marine biorefinery models must integrate fuel production with high-value co-products such as bioplastics, aquafeed protein, carotenoids, and exopolysaccharides, while maximizing waste-stream integration [44–46]. To evaluate these integrated systems, this critical narrative review synthesizes recent advancements across the entire marine microalgae processing chain. Section 2 details the methodological framework for literature selection and evaluation. Subsequently, this manuscript critically examines marine strain selection, stress-induced lipid biosynthesis, harvesting and cell disruption technologies, bioenergy conversion pathways, and integrated system-level sustainability (TEA/LCA) to identify key technical bottlenecks and outline priorities for industrial scaling.

2. Review Methodology

This review was conducted as a critical narrative review of recent research on marine microalgae for biofuel and integrated biorefinery applications. The literature search focused primarily on peer-reviewed studies published between January 2020 and December 2025, with emphasis on marine microalgal species, cultivation systems, lipid accumulation, harvesting and dewatering, cell disruption and extraction, biofuel conversion, techno-economic analysis (TEA), life-cycle assessment (LCA), and co-product valorization. The final literature search was conducted on 1 June 2026, and 136 records were identified and screened, with 46 records excluded during screening and 90 studies included in the final review.

Relevant literature was identified through searches of Scopus, Web of Science, and Google Scholar. Search terms were combined using Boolean operators and included combinations of "marine microalgae," "marine microalgal biorefinery," "microalgal biofuel," "lipid productivity," "lipid extraction," "harvesting," "dewatering," "cell disruption," "hydrothermal liquefaction," "transesterification," "pyrolysis," "techno-economic analysis," "life-cycle assessment," and "co-product valorization." Additional studies were identified by screening the reference lists of relevant review articles and primary research papers.

Studies involving freshwater, terrestrial, or otherwise non-marine microalgae were not treated as direct evidence for marine systems unless their findings addressed a general process principle that could reasonably inform marine microalgal processing.

Such studies are explicitly identified as general process evidence in the relevant tables and are interpreted cautiously; quantitative values from freshwater/general systems are not presented as marine performance benchmarks.

The selected literature was organized into interconnected themes covering (i) marine strain selection and biochemical characteristics, (ii) cultivation systems and productivity, (iii) lipid accumulation and stress strategies, (iv) harvesting and dewatering, (v) cell disruption and lipid extraction, (vi) biochemical and thermochemical conversion, (vii) TEA and LCA, and (viii) integrated biorefinery and co-product valorization. Quantitative results were extracted where reported, including biomass productivity, lipid content or productivity, harvesting efficiency, energy demand, conversion yield, biomass production cost, minimum fuel selling price, net energy ratio, and greenhouse-gas emissions.

Because the reviewed studies differed substantially in cultivation scale, strain characteristics, process configuration, system boundaries, functional units, energy sources, and economic assumptions, numerical values were not treated as universally comparable. Instead, reported values were interpreted within the methodological context of each study. Particular attention was therefore given to identifying trade-offs between biomass productivity and lipid accumulation, upstream cultivation performance and downstream energy demand, and fuel production and co-product recovery. The synthesis consequently emphasizes process-level interactions and identifies areas where additional pilot- and demonstration-scale evidence is required.

3. Selection of Marine Algae Species

Selecting appropriate microalgal strains dictates the efficiency of downstream harvesting and bioenergy conversion. Marine species are primarily selected based on their ability to withstand osmotic fluctuations, produce high neutral lipid fractions, and utilize natural seawater without requiring extensive nutrient supplementation [13, 14]. Oleaginous marine microorganisms are increasingly evaluated for their capacity to synthesize long-chain polyunsaturated fatty acids alongside triacylglycerols [47]. Figure 1 compares prominent marine algal species, including their structural characteristics and key target products, and the species are discussed below.

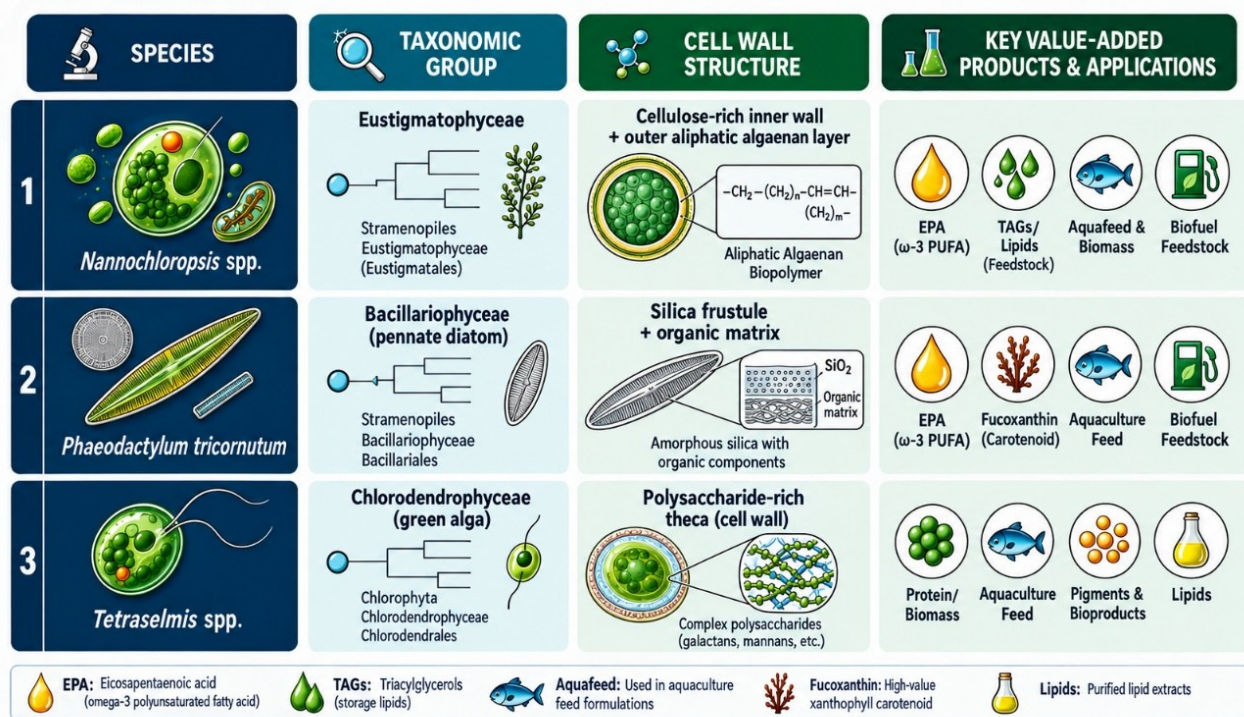


Figure 1. Comparative features of prominent marine algal species

- *Nannochloropsis* spp.: Species within this genus such as *N. oceanica* and *N. gaditana* serve as reference oleaginous platforms due to their high lipid content, which can exceed 50% of dry cell weight under nutrient deficiency [15, 48]. Their lipid fractions are rich in eicosapentaenoic acid (EPA) and triacylglycerols (TAGs), making them suitable for dual-purpose production of high-value nutraceuticals and fatty acid methyl esters (FAME) [15].
- *Phaeodactylum tricornutum*: As a model pennate diatom, *P. tricornutum* features a fully sequenced genome and established genetic tools [26]. Unlike green microalgae, diatoms possess a silica-based frustule rather than a thick cellulosic wall, which alters energy requirements during mechanical cell disruption [38]. It naturally synthesizes elevated levels of long-chain polyunsaturated fatty acids (LC-PUFAs) alongside TAG reserves [26].
- *Tetraselmis* spp.: Members of this genus, for instance *T. suecica*, are robust flagellated green algae characterized by rapid growth rates, higher tolerance to salinity variations, and larger cell sizes [17]. The larger cell size facilitates mechanical settling and flocculation during harvesting, although thick polysaccharide cell walls pose challenges for solvent-based lipid extraction [38, 39].

4. Algae Cultivation Strategies

Cultivation infrastructure choices dictate capital expenditure (CAPEX), operational expenses (OPEX), light conversion efficiency, biomass yields, and biological contamination risks. Formulating low-cost growth media using agricultural fertilizer components or aquaculture wastewater effluent can lower culture costs while maintaining biomass yields [49, 50].

Open Raceway Ponds (ORPs): ORPs require low capital expenditure, minimal operational energy, and simple construction [34]. However, they suffer from high evaporative water loss, poor light utilization efficiency, low volumetric biomass yields ($0.1\text{--}0.5\text{ g L}^{-1}$), and high vulnerability to wild biological contamination [6, 33]. Marine species cultivated in ORPs often require hyper-saline media to suppress wild biological competitors [51], as illustrated in Figure 2.

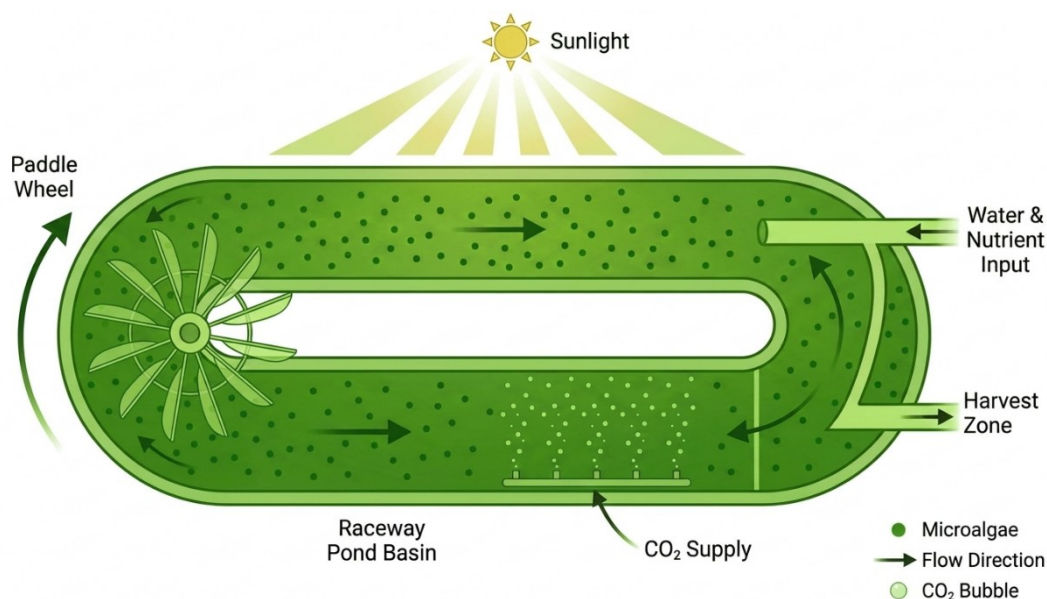


Figure 2. Open raceway pond system for large-scale microalgae cultivation

Closed Photobioreactors (PBRs): Tubular, flat-panel, or column PBRs provide precise control over temperature, pH, light intensity, and dissolved carbon dioxide levels [33]. They achieve significantly higher biomass densities ($2.0\text{--}8.0\text{ g L}^{-1}$) and prevent evaporation, but high capital expenditure and cooling requirements limit their widespread application for lower-value energy feedstocks [33, 34]. Representative physical configurations of closed PBR systems are shown in Figure 3.

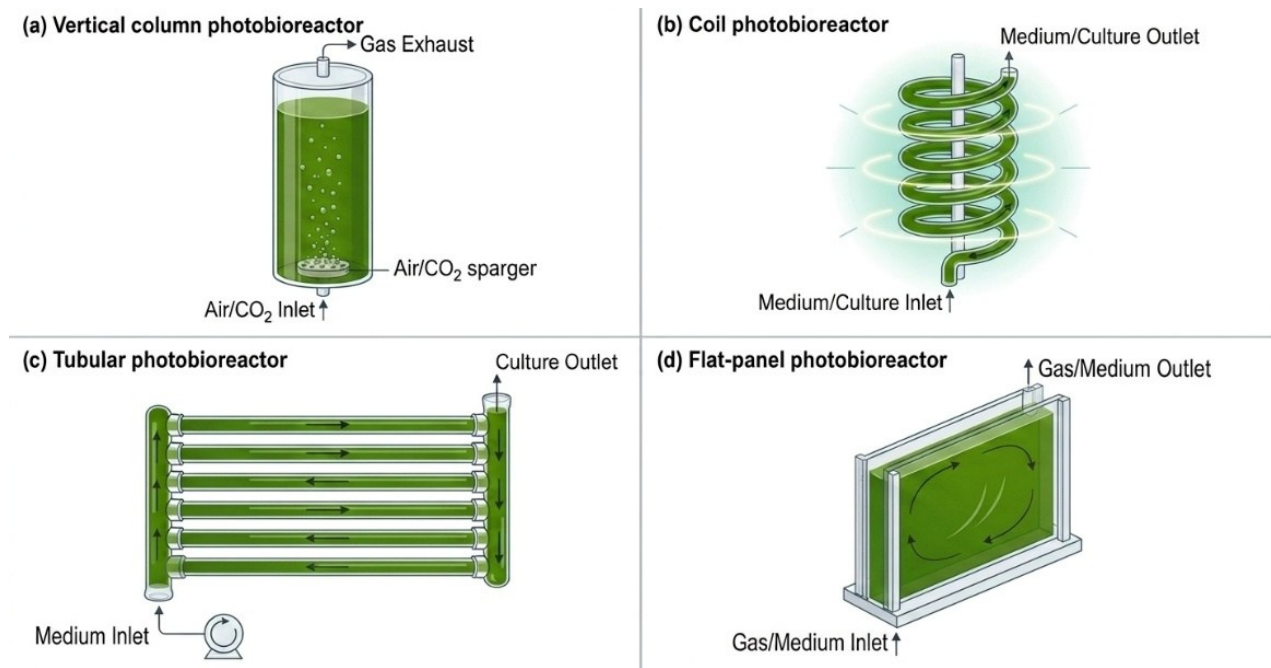


Figure 3. Representative configurations of closed photobioreactors for microalgae cultivation

Hybrid Cultivation Systems: Hybrid configurations separate biomass accumulation from lipid-induction or other product-forming stages. A common architecture uses a closed photobioreactor to build a controlled inoculum or high-density culture, then transfers it to an open raceway pond, where lower-cost operation and nutrient stress can drive product induction. A 2025 two-stage study using a non-marine *Scenedesmus* strain combined an airlift-driven tubular photobioreactor with an open raceway pond and reported increases in biomass and lipid content under optimized conditions [52]. This provides evidence for the general hybrid-process principle, but it should not be interpreted as direct evidence for marine strains. Marine-specific two-stage cultivation has not yet been directly demonstrated in the literature reviewed here, and remains an open question for future work. Remaining challenges include culture transfer, contamination control, hydraulic integration, and whether gains in biomass or lipid productivity justify the additional infrastructure.

Microfluidics and Algae-on-a-Chip: Microfluidic platforms provide controlled microscale environments for screening algal responses to light, nutrients, stressors, and other operating variables while reducing sample and reagent requirements. A 2025 microfluidic chip study demonstrated parallel cultivation of more than 30 microalgal cultures and in situ protein/lipid assessment, including Raman-based lipid characterization [53]. A separate 2025 review highlighted single-cell physiological and metabolic analysis as an important application area while noting that cost, materials, automation, and scale-up remain barriers [54]. These studies mainly concern general or non-marine microalgae; therefore, they support the methodological principle of high-throughput screening rather than direct prediction of marine cultivation performance. Table 1 summarizes a performance comparison of recent advancements across various marine microalgae cultivation systems.

Table 1. Summary of recent advancements in marine microalgae cultivation strategies (2020–2025).

Marine species	System & operating conditions	Verified biomass/productivity metric	Verified lipid metric	Reference / evidence basis
<i>Nannochloropsis oceanica</i>	Industrial-scale tubular PBR cultivation; 1-ha scenario evaluated in a Portuguese production model	27.61 t ha ⁻¹ y ⁻¹ at 1-ha scale	Not used as a quantitative lipid-content benchmark in the cited TEA; no value inferred	[34]; marine evidence

<i>Phaeodactylum tricornutum</i>	Optimized nutrient/light strategy; −50% N, +50% P and zero-Si treatments evaluated	95.92 mg L ^{−1} d ^{−1} biomass productivity under zero-Si	49.37 mg L ^{−1} d ^{−1} lipid productivity under zero-Si; +50% P reached 60.16 mg L ^{−1} d ^{−1}	[55]; marine evidence
<i>Tetraselmis suecica</i>	Cultivated using biogas-derived CO ₂ and anaerobically digested piggery effluent as nutrients; optimum pH 7.5	59.8 mg L ^{−1} d ^{−1} biomass productivity	25 mg L ^{−1} d ^{−1} lipid productivity	[56]; marine evidence

Note: Only quantitative values directly reported by the cited study are included. Values obtained under different strains, scales, nutrient regimes, or operating conditions should not be interpreted as directly comparable. "Not reported" indicates that the cited study did not provide a suitable quantitative value for the metric shown.

5. Lipid Production in Algae Cells

5.1 Lipid Induction by Abiotic Stress

Inducing storage lipid accumulation in marine microalgae relies on manipulating environmental parameters [23, 57]. Under nitrogen or phosphorus starvation, cells halt protein synthesis and redirect carbon flow toward neutral lipid accumulation, converting structural membrane lipids into TAGs stored within cytosolic lipid droplets [21, 25].

However, nitrogen depletion lowers photosynthetic yield and slows cell division, reducing overall volumetric biomass productivity [21, 22]. To mitigate this trade-off, two-phase cultivation systems are used: an initial nutrient-replete phase optimizes biomass accumulation, followed by a secondary nutrient-starved phase that triggers lipid accumulation [22, 25]. Manipulating light intensity, nutrient supply, and environmental parameters remains a primary operational aspect to trigger triacylglycerol accumulation in oleaginous cultures [58–60].

Salinity and light intensity adjustments also alter fatty acid composition [51, 57]. Hyper-saline conditions induce osmotic stress that stimulates lipid synthesis while increasing cellular glycerol levels [51, 61]. High light intensities generate reactive oxygen species (ROS), driving cells to store energy in TAGs as a photoprotective mechanism [23]. Iron deficiency similarly alters photosynthetic electron transport, driving lipid accumulation in microalgae [62].

5.2 Improvements in Algae Lipid Production

Molecular and ecological interventions are applied to bypass natural physiological limits on lipid accumulation [27, 29].

Targeted Genetic Engineering: Overexpressing key enzymes in the Kennedy pathway such as type-2 diacylglycerol acyltransferase (DGAT2) has successfully increased TAG content in *P. tricornutum* without impairing cellular growth [26, 28]. Metabolic engineering efforts also target transcription factors regulating fatty acid synthesis to increase total lipid productivity [28, 63]. Advances in genetic manipulation provide powerful pathways to bypass trade-offs between cell growth and lipid synthesis [64, 65].

Adaptive Laboratory Evolution (ALE): Subjecting strains to long-term osmotic or oxidative stress selects for mutated populations with enhanced lipid yields and environmental tolerance without requiring foreign gene insertion [29].

Phycosphere and Microbiome Interactions: Co-culturing microalgae with plant-growth-promoting bacteria (PGPB) improves nutrient uptake and biomass accumulation [66]. Specific bacterial signaling molecules, such as diketopiperazines, stimulate cell growth and lipid synthesis in marine diatoms, offering a chemical strategy to enhance yields without genetic modification [31].

6. Harvesting and Dewatering Technologies

The dilute nature of marine microalgal cultures poses a major midstream processing hurdle [35, 36]. Cultivation media typically contain 0.2–3 g L⁻¹ dry biomass in open ponds and photobioreactors, meaning over 99% of the liquid volume must be removed before downstream extraction [35, 36]. Processing these high fluid volumes requires multi-stage harvesting protocols that combine primary thickening with secondary dewatering [35, 36], as illustrated in Figure 4. Table 2 summarizes the major harvesting and dewatering methods, along with their reported performance, advantages, and principal drawbacks. Researchers have explored innovative harvesting strategies, including microalgal biofilm cultivation, to simplify primary dewatering and reduce operational energy inputs [37].

Flocculation: Primary recovery often utilizes inorganic coagulants or organic polymers to neutralize negative cell surface charges, causing microalgae to aggregate into larger flocs [35, 36]. Auto-flocculation induced by elevating pH via sodium hydroxide addition offers a low-cost alternative, though chemical residue in the harvested biomass can affect downstream catalytic conversion [36, 67]. Bio-flocculation using bacterial or fungal co-cultures avoids chemical contamination and reduces operating expenses [36, 66].

Filtration and Centrifugation: Secondary dewatering relies on physical separation techniques [35, 37]. Continuous centrifugation is widely used for rapid, high-efficiency cell recovery, but high electrical power demands make it cost-prohibitive as a primary separation step for low-value bioenergy [34, 36]. Membrane filtration achieves high recovery efficiency without thermal degradation, though membrane fouling by extracellular polymeric substances requires periodic backwashing [36, 68].

Table 2. Comparison of major harvesting and dewatering methods relevant to marine microalgae

Harvesting/dewatering method	Verified quantitative efficiency/performance	Major advantages	Principal drawbacks	Reference(s)
Flocculation	78.82% flocculation efficiency after 48 h in a <i>Nannochloropsis oculata</i> – <i>Phaeodactylum tricornutum</i> co-culture.	Simple primary thickening; can reduce downstream dewatering load	Chemical residues and condition-dependent performance	[69]; [36]; [35]; [67]; general/mixed evidence
Bio-flocculation	No single efficiency value retained because the cited literature summarizes multiple biological systems rather than one standardized marine experiment.	Avoids addition of inorganic coagulants; potential reduction in operating inputs	Biological interactions and process stability require control	[66]; [36]; general/mixed evidence
Centrifugation	A quantitative recovery value is not retained here because the cited marine-specific TEA reports centrifugation as a downstream operation but does not provide a single universal recovery efficiency.	Rapid separation; suitable for secondary dewatering	High electricity demand and cost sensitivity	[34]; [36]; marine/general evidence
Membrane filtration	No single recovery percentage retained; the cited sources describe high recovery but performance varies with membrane type and fouling.	High retention; avoids thermal treatment	Fouling and backwashing requirements	[68]; [36]; general/mixed evidence

Microalgal biofilm cultivation	A 2024 primary study reported 91.6% cell recovery from a 3D porous substrate; ultrasonic assistance increased the detachment rate by 143.45%, reaching $41.07 \text{ g m}^{-2} \text{ h}^{-1}$.	Can reduce the volume of suspended culture requiring bulk dewatering	Requires suitable attachment/detachment surfaces and stable biofilm operation	[70]; [37]; general microalgal evidence
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Note: Harvesting and dewatering performance depends on biomass concentration, process conditions, and system scale.

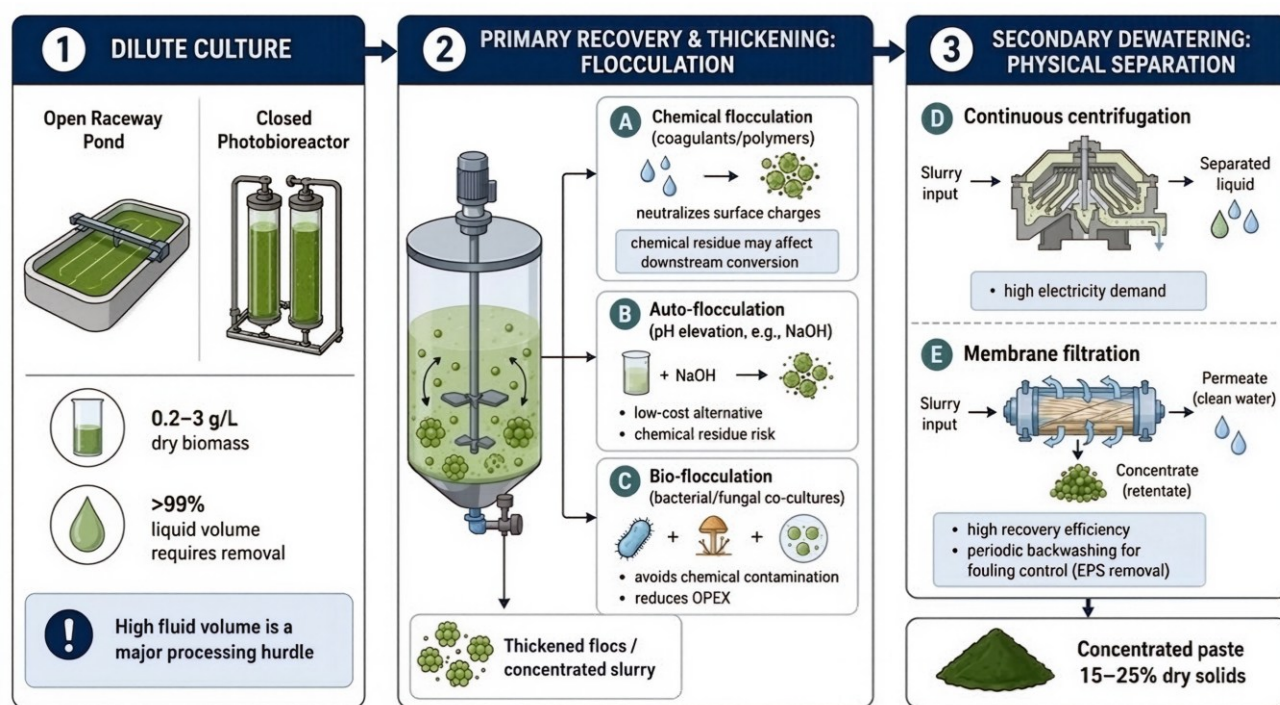


Figure 4. Multi-stage harvesting and dewatering pipeline for marine microalgae cultures, showing primary flocculation methods and secondary physical separation techniques.

7. Cell Wall Disruption Methods

Once concentrated into a thick paste (15–25% dry solids), microalgae must undergo cell disruption to release intracellular lipid droplets [35, 39]. The required mechanical force depends directly on the cell wall's structural composition [38, 39]. For example, *Nannochloropsis* species possess an outer algaenan layer that resists chemical hydrolysis, whereas diatoms like *Phaeodactylum tricornutum* feature silica-based frustules that crack under lower mechanical shear [26, 38].

Mechanical Disruption: High-pressure homogenization (HPH) and bead milling break cell walls via high shear stress, cavitation, and rapid pressure drops [38, 39]. These methods achieve high disruption rates without adding chemical contaminants, but their high electrical consumption increases processing expenses [34, 39]. Hydrodynamic cavitation and ultrasound-assisted disruption create micro-bubbles that collapse near cell surfaces, creating localized shockwaves that rupture cell membranes [39].

Non-Mechanical and Enzymatic Disruption: Enzymatic lysis uses specific cellulases, pectinases, or proteases to degrade cell wall polymers under mild temperature and pH conditions [38, 39]. While enzymatic hydrolysis avoids lipid oxidation and requires lower energy inputs, the cost of commercial enzymes limits large-scale application [34, 39]. Osmotic shock and microwave-assisted heating rapidly alter cell membrane permeability, speeding solvent penetration during extraction [39, 40].

8. Lipid Extraction Techniques and Green Solvents

Conventional analytical lipid extractions rely on binary organic solvent mixtures, such as chloroform-methanol or hexane-isopropanol systems [39, 40]. Organic solvents penetrate the cell matrix, disrupt hydrophobic interactions, and dissolve neutral lipids and polar membrane lipids [16, 39]. However, the volatility, toxicity, and environmental impact of chlorinated solvents preclude their use in commercial biorefineries [39, 40].

Process development has shifted toward green extraction alternatives:

Supercritical Fluid Extraction (scCO₂): Carbon dioxide in its supercritical state ($T > 31.1\text{ }^{\circ}\text{C}$, $P > 7.38\text{ MPa}$) acts as a non-polar, non-toxic solvent with liquid-like solvating power and gas-like diffusivity [39, 40]. Adding ethanol as a polar co-solvent improves the recovery of amphiphilic lipids and pigments [19, 39]. scCO₂ yields high-purity lipid extracts without leaving solvent residues, though elevated capital equipment costs present a barrier to deployment [34, 39].

Switchable Hydrophilicity Solvents (SHS) and Ionic Liquids (ILs): SHS compounds change solubility from hydrophobic to hydrophilic upon exposure to carbon dioxide, simplifying solvent recovery without energy-intensive distillation [39, 40]. Ionic liquids and deep eutectic solvents disrupt cell walls and dissolve specific lipid fractions at ambient temperatures, though solvent recycling remains a key technical challenge [39].

Wet Biomass Processing: To eliminate thermal drying costs, processing wet microalgae slurry directly via subcritical water extraction or hydrothermal liquefaction (HTL) avoids the major energy barrier of complete dewatering [41, 42].

9. Bioenergy Conversion Pathways

The choice of conversion technology determines the chemical characteristics of the final biofuel, overall process energy efficiency, and co-product viability [41, 42, 71]. Bioenergy conversion from marine microalgae proceeds primarily through biochemical routes (transesterification) or thermochemical processing (hydrothermal liquefaction and pyrolysis) [67, 71, 72], as illustrated in Figure 5.

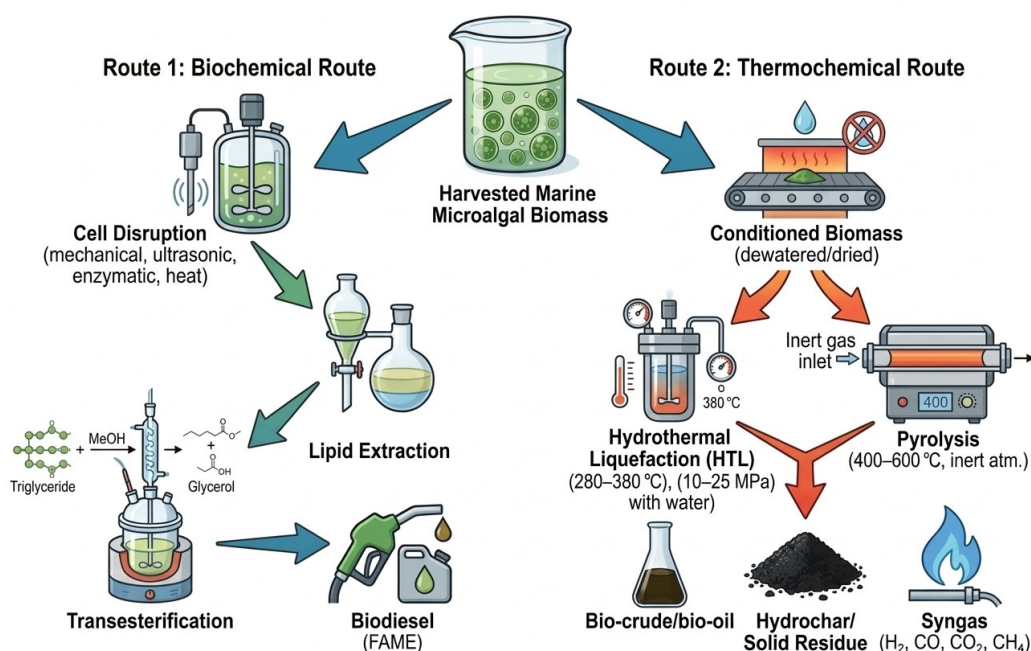


Figure 5. Biochemical and thermochemical processing routes for microalgae bioenergy conversion

9.1 Biodiesel Production through Transesterification

Transesterification remains the standard chemical pathway for converting extracted microalgal lipids into fatty acid methyl esters (FAME) or biodiesel [67, 72]. In this reaction, triacylglycerols (TAGs) react with a short-chain alcohol, typically methanol, in the presence of a catalyst to yield FAME and glycerol as a side product [67, 72]. Simultaneous co-production of biodiesel and bioethanol from whole algal biomass or specialized strains improves overall energy recovery across conversion pathways [73, 74].

Catalyst Selection: Traditional homogeneous catalysts like sodium hydroxide or sulfuric acid offer high reaction rates, but washing steps generate large volumes of wastewater and complicate glycerol purification [67]. Heterogeneous solid catalysts, including metal oxides, calcined eggshells, and biochar-supported acid or base systems, allow easier catalyst recovery, reduce equipment corrosion, and permit continuous operation [67].

Direct (In Situ) Transesterification: To streamline processing, in situ transesterification combines lipid extraction and esterification into a single step by treating dry or semi-wet biomass directly with alcohol and acid catalysts [72]. This process bypasses solvent extraction, reducing solvent use and processing time [40, 72].

Fuel Quality Parameters: Marine microalgae rich in saturated and monounsaturated fatty acids yield biodiesel with favorable cetane numbers and oxidative stability [16, 17]. However, high concentrations of polyunsaturated fatty acids (PUFAs), common in *Phaeodactylum tricornutum*, can reduce oxidative stability and require mild hydrotreating to meet commercial fuel standards [16, 20, 26].

9.2 Hydrothermal Liquefaction (HTL)

Hydrothermal liquefaction operates under subcritical to near-critical water conditions ($T = 280\text{--}380\text{ }^{\circ}\text{C}$, $P = 10\text{--}25\text{ MPa}$), converting whole biomass slurry into a high-energy bio-crude oil alongside aqueous, gaseous, and solid biochar fractions [41, 42].

Elimination of Drying Steps: HTL directly processes wet microalgal biomass (containing 15–20% solids), eliminating the high energy penalty associated with thermal drying [41, 42].

Whole-Biomass Conversion: Unlike transesterification, which processes isolated neutral lipids, HTL breaks down cellular proteins, carbohydrates, and structural lipids simultaneously into bio-crude [41, 42]. This increases overall mass conversion yields, making HTL well-suited for high-protein marine strains like *Tetraselmis* [17, 75].

Aqueous Phase Recycling: The HTL process generates an aqueous co-product rich in nitrogen, phosphorus, and organic carbon [41, 42]. Recycling this aqueous phase back into microalgae cultivation ponds supplies essential nutrients, lowering fertilizer costs and improving overall life-cycle energy metrics [42, 76].

9.3 Isothermal Pyrolysis

Pyrolysis thermally degrades dry microalgal biomass in the absence of oxygen at temperatures between $400\text{ }^{\circ}\text{C}$ and $600\text{ }^{\circ}\text{C}$ [5, 71]. Isothermal pyrolysis yields bio-oil, non-condensable synthesis gas (CO , CO_2 , H_2 , CH_4), and solid biochar [5, 71]. Integrating alternative energy inputs, such as solar thermal heating, into thermochemical conversion processes like gasification or pyrolysis enhances system energy balances [77].

Yield and Bio-Oil Characteristics: Bio-oil produced via microalgae pyrolysis has a higher heating value (HHV) than terrestrial biomass bio-oil because of its lower oxygen content [5, 71]. However, high protein levels in algal biomass can introduce nitrogen-

containing compounds into the bio-oil, which may require catalytic hydrodeoxygenation and hydrodenitrogenation to improve fuel quality and produce transportation-fuel-range products [41, 71].

Biochar Applications: The solid biochar fraction produced during marine microalgae pyrolysis contains mineral elements derived from seawater and biomass [7, 71]. This biochar can serve as a soil amendment, an adsorbent for heavy metal remediation, or a solid fuel for co-combustion [7, 38, 71]. Residual biomass hydrolysate remaining after extraction can also be utilized as a carbohydrate feedstock for secondary microbial lipid synthesis by oleaginous yeasts [78]. Table 3 summarizes recent technological advancements in marine microalgae bioenergy conversion routes.

Table 3. Recent technological advancements in microalgae bioenergy conversion routes relevant to marine systems.

Conversion Pathway	Technological Advancement	Process Improvement & Benefits	Verified quantitative outcome	Reference
Transesterification	Heterogeneous catalysts can facilitate catalyst recovery and reduce washing/corrosion burdens.	No single conversion percentage is retained because the cited literature is a review of multiple catalyst systems rather than a single, directly comparable experiment.	Not retained; no directly comparable quantitative value was verified for this review-level entry.	[67]; [72]; general microalgal evidence
In situ transesterification	Combines lipid release/extraction and esterification in one operation and can reduce solvent use.	The previously stated energy-reduction percentage was removed because it was not directly supported by the cited review.	Not retained; no directly comparable quantitative value was verified for this review-level entry.	[72]; [40]; general microalgal evidence
Hydrothermal liquefaction (HTL)	Wet biomass can be processed without complete thermal drying; aqueous nutrient recovery is a potential integration route.	A universal bio-crude yield range was removed because HTL yield varies with feedstock and operating conditions and the cited review does not support a single range as a universal value.	Not retained; no universal quantitative yield was verified for this review-level entry.	[42]; [41]; general microalgal evidence
Isothermal pyrolysis	Pyrolysis can convert dry algal biomass into bio-oil, gas and char; catalytic upgrading can improve oil quality.	No single HHV or nitrogen-reduction value retained because these outcomes are feedstock- and catalyst-specific.	Not retained; no directly comparable quantitative outcome was verified for this review-level entry.	[71]; [5]; marine/general evidence

Note: Conversion yields and efficiencies depend on feedstock characteristics and process conditions and should be interpreted within the context of each study.

10. Techno-economic Analysis (TEA) and Cost Factors

Techno-economic studies generally indicate that dedicated single-product microalgal biofuel facilities remain economically challenging under many current assumptions [42, 43, 79]. Capital expenditures (CAPEX) for photobioreactors and raceway pond installation remain high, while operational expenditures (OPEX) are driven up by electricity demands for mixing, harvesting, and water pumping [33, 34, 36].

Fuel-conversion configuration can also substantially affect the estimated selling price. Gu et al. [80] reported minimum fuel selling prices of approximately US\$1.61 L⁻¹ and US\$2.10 L⁻¹ for two-stage and one-stage hydrothermal liquefaction configurations, respectively, using the same microalgal feedstock. The two-stage configuration also reduced the estimated

installed capital cost from approximately US\$112 million to US\$89 million and increased the reported energy return on energy invested from 5.31 to 6.73 [80].

Reported minimum fuel selling prices (MFSP) for microalgal biodiesel and bio-crude can exceed comparable petroleum-fuel prices, depending on the system boundaries and assumptions used [42, 43]. Economic modeling indicates that major cost reductions depend on three factors: achieving higher cellular lipid productivities in large-scale cultures, utilizing low-cost continuous dewatering systems, and transitioning from single-fuel production to multi-product biorefinery architectures [36, 43, 79]. Techno-economic modeling across industrial microalgae processes consistently demonstrates that high capital requirements and energy demands restrict economic feasibility [81, 82].

Quantitative techno-economic results illustrate the strong influence of cultivation and downstream processing on microalgal biomass cost. Vázquez-Romero et al. [34] estimated a production cost of €53.32 kg⁻¹ dry biomass for *Nannochloropsis oceanica* at a 1-ha scale, with an annual productivity of 27.61 t ha⁻¹ y⁻¹. An alternating *Tisochrysis lutea* and *Phaeodactylum tricornutum* cultivation system produced 12.94 t ha⁻¹ y⁻¹ and had an estimated biomass cost of €105.19 kg⁻¹. For *N. oceanica*, the modeled energy requirement was 50.82 kWh kg⁻¹ dry biomass. Centrifugation and ultrafiltration required 28.53 and 25.83 kWh kg⁻¹ dry biomass, respectively, while combining ultrafiltration with spray drying produced an estimated biomass cost of €49.57 kg⁻¹. Scaling the *N. oceanica* system from 1 to 10 ha was projected to reduce production cost by 17.99% [34].

More recent modeling has focused specifically on cultivation-stage economics. A 2025 techno-economic analysis of batch and semi-continuous open-raceway-pond cultivation strategies reported a minimum biomass selling price (MBSP) of US\$1130–1200 per metric tonne for semi-continuous cultivation, compared with US\$1380–2040 per metric tonne for batch cultivation, with the difference driven primarily by seed-train costs; semi-continuous systems remained cost-competitive only when mean-time-to-failure exceeded approximately 26 days [83]. This study modeled a freshwater reference strain rather than a marine species, so these cost values are treated as general cultivation-economics evidence rather than a marine-specific benchmark; nevertheless, the finding that seed-train design and culture stability strongly influence biomass production cost is directly relevant to marine cultivation economics.

11. Life-Cycle Assessment (LCA) and Environmental Footprints

Life-cycle assessments evaluate fossil energy inputs, net greenhouse gas (GHG) emissions, and environmental impacts across the full value chain [43, 79]. Marine microalgae offer clear environmental benefits over terrestrial feedstocks because they can reduce direct competition for arable land and freshwater [3, 14]. Furthermore, using seawater can reduce the freshwater demand associated with microalgal cultivation [13]. Life-cycle assessments have also been applied to emerging microalgal applications, including algae-based coatings for direct air carbon capture and assessments of social sustainability in resource recovery facilities [84, 85].

Bradley et al. [43] reported a net energy ratio (NER, defined as direct energy input divided by the energy content of the fuel produced) of 0.99 when co-product energy content was credited against the system's energy input, rising to 1.03 when the system boundary was widened to include energy embedded in feedstock chemical production across the wider value chain. Including infrastructure, the study estimated GWP100 values of 0.256, 0.238, and 0.148 kg CO₂-eq MJ⁻¹ across its assessed electricity-supply scenarios, compared with 0.0884 kg CO₂-eq MJ⁻¹ for petroleum diesel. The study identified electricity consumption and infrastructure as major contributors to environmental impacts and showed that increasing microalgal productivity was the most effective strategy for reducing GWP100. Chen and Quinn [42] similarly reported a baseline GWP of 23 g CO₂-eq MJ⁻¹ and a NER of 0.30 for an HTL-based microalgal biofuel system, with nutrient recycling included among the parameters evaluated in their scenario analysis. These results demonstrate that the environmental performance of microalgal biofuels is highly sensitive to electricity demand, biomass productivity, infrastructure, conversion efficiency, and nutrient management.

A 2025 geographically resolved techno-economic and life-cycle assessment of hydrothermal liquefaction (HTL) and hydroprocessed ester and fatty acids (HEFA) pathways across the United States reported baseline minimum fuel selling prices

(MFSP) of US\$3.72–7.26 L⁻¹ for HTL and US\$5.79–10.93 L⁻¹ for HEFA, decreasing to US\$1.48–4.10 L⁻¹ and US\$1.73–4.48 L⁻¹, respectively, under future scenarios with increased lipid content and reduced carbon dioxide delivery costs; optimization analysis identified pathways toward an MFSP of US\$0.75 L⁻¹ with approximately 70% greenhouse-gas emission reductions relative to petroleum fuels [86]. As with other reviewed TEA/LCA studies, this analysis was based on a freshwater/general cultivation model rather than a marine strain, and its results depend strongly on regional productivity, meteorological conditions, and feedstock-delivery logistics; it is included here as general process and methodological evidence reflecting current (2025) TEA/LCA benchmarks rather than as a marine-specific performance value.

Table 4 summarizes selected quantitative TEA and LCA results reported in the reviewed literature. The reported values vary substantially across cultivation and conversion configurations and should therefore be interpreted within each study's methodological context. Differences in system boundaries, process configuration, scale, energy supply, functional units, and co-product treatment limit direct numerical comparison.

Table 4. Comparison of reported techno-economic and life-cycle performance of microalgal biofuel systems relevant to marine microalgal biorefineries

Study	System / pathway	Main TEA metric(s)	Main LCA / energy metric(s)	Key finding	Major sensitivity / limitation
[80] [Freshwater/ general evidence]	Hydrothermal liquefaction (HTL); one-stage vs two-stage	MFSP: US\$2.10 vs US\$1.61 L ⁻¹ ; installed CAPEX: US\$112 million vs US\$89 million	EROEI: 5.31 vs 6.73	Two-stage HTL improved modeled economic and energy performance.	Depends on HTL configuration and process/economic assumptions.
[42] [General process evidence]	HTL-based microalgal biofuel	Conversion cost: ~US\$0.45 L ⁻¹ gasoline equivalent	NER: 0.30; GWP: 23 g CO ₂ -eq MJ ⁻¹	Strong dependence on process assumptions.	Thermodynamic assumptions changed cost by ~US\$0.07 L ⁻¹ ; NER depends on system boundary and definition.
[34] [Marine evidence]	<i>Nannochloropsis oceanica</i> cultivation, harvesting and drying	€53.32 kg ⁻¹ dry biomass at 1 ha; €49.57 kg ⁻¹ with ultrafiltration + spray drying	50.82 kWh kg ⁻¹ dry biomass total; centrifugation 28.53 kWh kg ⁻¹ ; ultrafiltration 25.83 kWh kg ⁻¹	Harvesting and downstream processing can dominate energy and cost; scaling from 1 to 10 ha reduced modeled cost by 17.99%.	Scale, harvesting, drying and productivity assumptions.
[43] [General/ind ustrial microalgal evidence]	Microalgal biodiesel; data from an operating 1-ha facility	Not reported; LCA-focused study	NER: 0.99 with co-product energy; 1.03 with wider value-chain energy. GWP100: 0.256, 0.238 and 0.148 kg CO ₂ -eq MJ ⁻¹ across electricity scenarios.	Electricity and infrastructure were major impact contributors; increasing productivity was the most effective strategy for reducing GWP100.	Electricity supply, infrastructure, productivity and co-product treatment.
[86] [General/fre shwater microalgal evidence]	Geographically resolved HTL and HEFA renewable diesel/SAF pathways, United States	Baseline MFSP: US\$3.72–7.26 L ⁻¹ (HTL); US\$5.79–10.93 L ⁻¹ (HEFA). Optimized scenarios: US\$1.48–4.10 L ⁻¹	Optimization pathway to MFSP of US\$0.75 L ⁻¹ with ~70% GHG emission reduction vs. petroleum fuels.	Increased lipid content and reduced CO ₂ -delivery costs substantially lower projected fuel costs; feasibility is strongly	Regional productivity, meteorology, feedstock lipid content, and CO ₂ -delivery

(HTL); US\$1.73–4.48 L ⁻¹ (HEFA).	geography- dependent.	infrastructure assumptions.
Note: TEA, techno-economic analysis; LCA, life-cycle assessment. Quantitative values are reproduced only when directly supported by the cited study. Evidence basis is identified in the Study column. Freshwater/general microalgal results are not treated as marine performance benchmarks. Reported values remain study-specific and depend on system boundaries, process configuration, scale, energy supply, and co-product treatment.		

12. Multi-Product Biorefining and Circular Economy Models

To offset high processing expenses, modern facility designs employ a low-waste cascading biorefinery [46, 75, 87]. Instead of extracting lipids and discarding the remaining biomass, different cellular fractions can be recovered and valorized into multiple products [46, 88]. Applying life-cycle assessment frameworks to agricultural bio-products, such as microalgae-based bio-fungicides, supports zero-waste circular bioeconomy goals [89], as outlined in the multi-product biorefinery workflow (Figure 6).

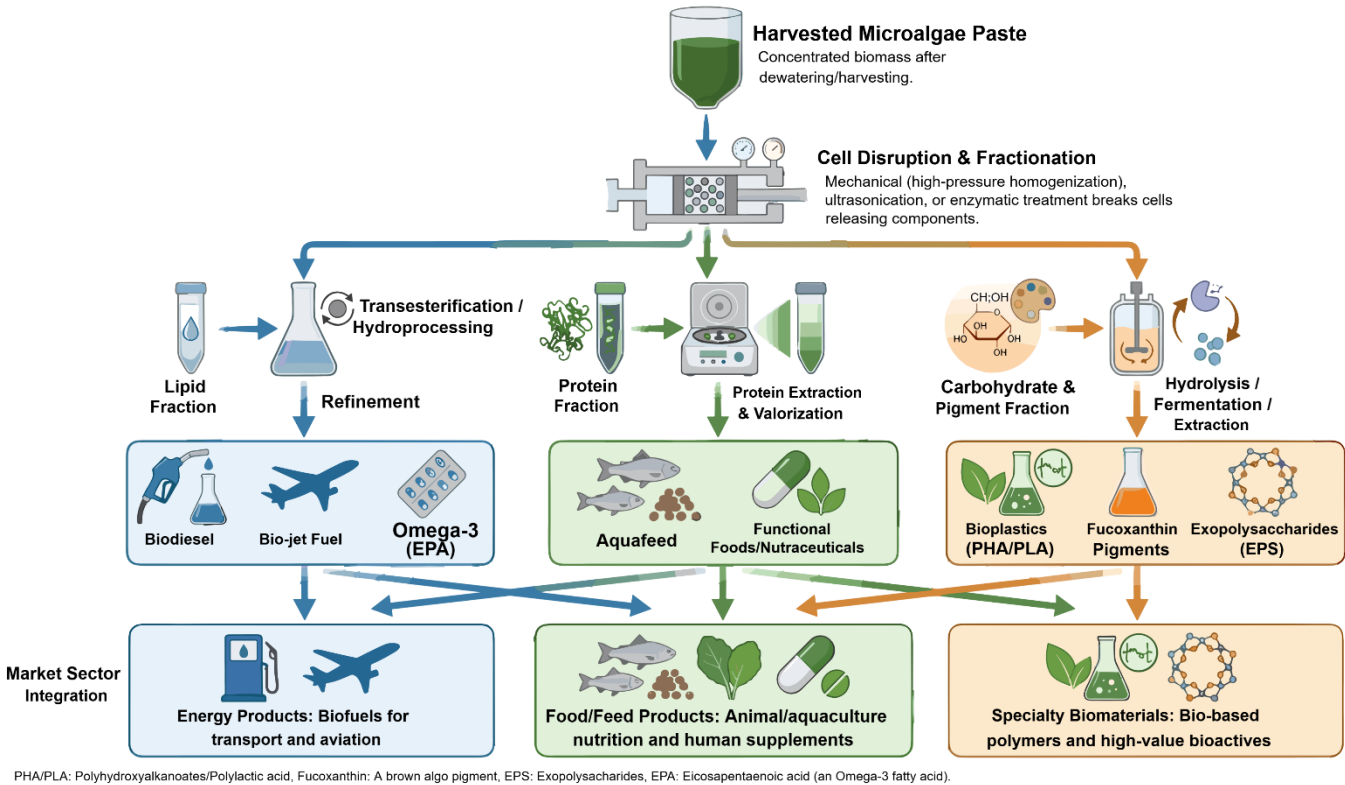


Figure 6. Multi-product biorefinery workflow for fractionating microalgal biomass into lipid, protein, and carbohydrate/pigment streams.

High-Value Co-Products: Marine taxa produce valuable bioactive compounds [18, 19]. *Nannochloropsis* and *Phaeodactylum tricornutum* accumulate high concentrations of eicosapentaenoic acid (EPA) and carotenoids such as fucoxanthin, which can have relatively high commercial value in nutraceutical markets [16, 17]. Protein-rich residual biomass obtained after lipid extraction has potential for use as an alternative protein ingredient in aquaculture feeds [19, 87]. Additionally, carbohydrates extracted from green microalgae like *Tetraselmis* can be converted into bioethanol or biodegradable bioplastics [46, 75].

Waste Stream Integration: Integrating microalgae cultivation with industrial processes can reduce resource requirements by utilizing waste carbon dioxide and nutrient-rich wastewater streams. Coupling microalgal cultivation with flue-gas treatment provides a potential source of concentrated CO₂ while simultaneously supporting biological carbon utilization [44, 45]. Domestic

wastewater can also serve as a water and nutrient source for microalgal cultivation, although nutrient composition and inhibitory compounds must be evaluated and additional nutrients or pretreatment may be required [44].

13. Limitations and Uncertainties in Reviewed Studies

Differences in experimental scale, process assumptions, system boundaries, and data quality constrain interpretation of techno-economic and life-cycle results for marine microalgal biorefineries. Many published assessments use laboratory- or pilot-scale measurements that are extrapolated to commercial production. Such extrapolations introduce uncertainty because culture stability, contamination, mixing, temperature control, harvesting efficiency, and equipment utilization can change substantially with scale [34, 43].

Biomass productivity is a particularly important source of uncertainty because it determines the quantity of biomass available to distribute cultivation and infrastructure costs. Lipid content alone also does not provide a sufficient basis for evaluating biofuel performance because high lipid accumulation can occur simultaneously with reduced biomass productivity. Experimental studies of *Phaeodactylum tricornutum*, for example, have reported substantial variation in lipid productivity under different nutrient conditions, demonstrating the sensitivity of performance to cultivation conditions. Consequently, TEA results based on different productivity assumptions may produce substantially different estimates of fuel cost and economic feasibility [55].

Downstream processing introduces additional uncertainty because harvesting, dewatering, drying, cell disruption, and extraction requirements depend on culture concentration, biomass characteristics, and process configuration. Vázquez-Romero et al. [34] reported an energy requirement of 50.82 kWh kg⁻¹ dry biomass for *Nannochloropsis oceanica*, while centrifugation and ultrafiltration accounted for 28.53 and 25.83 kWh kg⁻¹ dry biomass, respectively. The same study estimated a biomass production cost of €53.32 kg⁻¹ dry biomass at a 1-ha scale and found that scaling the system from 1 to 10 ha could reduce production cost by 17.99%. These values illustrate the influence of processing configuration and plant scale, but they should not be interpreted as universal values for all marine microalgal systems.

LCA results are similarly sensitive to methodological choices. Electricity mix, nutrient source, carbon dioxide supply, transportation, infrastructure, co-product allocation, functional unit, and system boundaries can all affect calculated energy balances and greenhouse-gas emissions. Bradley et al. [43], using data from an operating one-hectare facility, demonstrated the importance of real-world operating information when evaluating microalgal biodiesel systems. Their results also showed that electricity consumption and infrastructure contributed substantially to environmental impacts, indicating that improvements in biomass productivity alone may not eliminate all environmental burdens.

TEA results are affected by capital costs, plant scale, financing assumptions, energy prices, biomass productivity, product yields, co-product revenues, and the method used to calculate minimum fuel selling price. Chen and Quinn [42], for example, estimated a baseline HTL conversion cost of US\$0.45 L⁻¹ gasoline equivalent and a net energy ratio of 0.30 under their defined system boundary. Their sensitivity analysis showed that alternative thermodynamic assumptions could change the estimated conversion cost by approximately US\$0.07 L⁻¹. Gu et al. [80] likewise reported different minimum fuel selling prices for alternative HTL configurations, illustrating how sensitive economic performance is to process design and conversion strategy.

Direct comparison among studies is further complicated by differences in how energy indicators are defined and which functional units are selected. For example, NER may be defined differently across studies, with some formulations expressing energy output relative to energy input and others using the reciprocal relationship. Therefore, an NER value should not be interpreted without first examining the equation, system boundary, and energy flows used by the study. Future TEA and LCA studies should report these methodological details, along with key assumptions, sensitivity analyses, and uncertainty ranges, to improve comparability and reproducibility.

Overall, the reviewed evidence indicates that reported TEA and LCA values should be interpreted as scenario-specific estimates rather than universal performance indicators. Greater use of long-term pilot- and demonstration-scale data, standardized system

boundaries, transparent assumptions, sensitivity analysis, and uncertainty quantification would improve the reliability of future assessments of marine microalgal biorefineries.

14. Key Technological Bottlenecks

The reviewed literature identifies several interconnected technological bottlenecks that continue to influence the scale-up of marine microalgal bioenergy systems [8, 20]. Physiological trade-offs between biomass growth and lipid accumulation can limit overall lipid productivity, particularly under nutrient or other abiotic stresses [21, 25]. Harvesting and dewatering remain important process constraints because marine cultures are relatively dilute and require substantial water removal before conventional downstream processing [36, 37]. Lipid recovery is further affected by cell-wall structure and the energy and solvent requirements associated with cell disruption and extraction [38–40]. Thermochemical conversion can reduce the need for complete drying, but nitrogen- and oxygen-containing compounds in algal bio-crude may require additional catalytic upgrading to improve fuel quality [20, 71]. These bottlenecks are interdependent, indicating that future process improvements should be evaluated at the integrated biorefinery level rather than as isolated improvements to individual unit operations.

15. Future Perspectives

Advancing marine microalgal bioenergy systems requires coordinated progress in strain development, cultivation, downstream processing, conversion technologies, and biorefinery integration. Based on the limitations identified in the reviewed literature, several research priorities emerge. Genetic and metabolic engineering approaches, including CRISPR-Cas9 and synthetic biology, could be explored to enhance lipid biosynthesis while minimizing growth penalties [26, 28]. Co-cultivation and microbiome optimization may improve cellular growth and stress resilience through beneficial interactions between microalgae and associated bacteria, although their stability under large-scale cultivation conditions requires further investigation [31, 66]. Future studies should also prioritize low-energy dewatering and green extraction methods that can reduce energy consumption and dependence on hazardous solvents [36, 40]. Thermochemical processes, particularly hydrothermal liquefaction, require further refinement through optimizing aqueous-phase nutrient recycling and catalytic upgrading to improve bio-crude quality and facilitate conversion into transportation fuels [41, 42]. At the system level, pilot- and demonstration-scale integrated biorefineries should evaluate the combined utilization of waste carbon dioxide, wastewater resources, and high-value co-product recovery to assess their effects on economic and environmental performance [43, 45, 46]. Finally, artificial intelligence and machine-learning approaches could support strain selection, cultivation optimization, process monitoring, and prediction of operating conditions, although industrial-scale application remains limited [90].

16. Conclusions

Marine microalgae represent a promising third-generation biofuel platform with the potential to reduce dependence on freshwater resources and arable land while enabling the production of fuels and higher-value bioproducts. Genera such as *Nannochloropsis*, *Tetraselmis*, and *Phaeodactylum tricornutum* have received particular attention because their biochemical characteristics support both lipid-based and thermochemical conversion pathways. However, their performance varies considerably with species, nutrient availability, light conditions, and cultivation strategy. The reviewed evidence indicates that lipid content alone is insufficient to assess biofuel potential; an integrated biorefinery framework must evaluate biomass productivity, lipid productivity, cultivation stability, harvesting efficiency, downstream energy demand, conversion efficiency, and co-product recovery.

Techno-economic and life-cycle evidence further shows that the feasibility of marine microalgal biofuel production depends strongly on process configuration and system assumptions. Reported biomass production costs, energy requirements, net energy ratios, greenhouse-gas emissions, and fuel selling prices vary substantially across cultivation and conversion pathways. Harvesting and dewatering remain major constraints because large volumes of culture medium must be processed before downstream conversion, while cell disruption, lipid extraction, drying, and thermochemical upgrading can impose additional energy and processing demands. Nevertheless, process integration offers opportunities to improve resource efficiency through

co-product recovery, wastewater utilization, carbon dioxide recycling, and other circular-economy strategies where technically and economically feasible. Thus, assess the performance of marine microalgal biofuels at the complete biorefinery level rather than through individual cultivation or conversion steps in isolation.

Several uncertainties continue to limit direct comparison among published studies. Differences in cultivation scale, biomass productivity assumptions, electricity sources, nutrient inputs, harvesting technologies, conversion efficiencies, co-product allocation, functional units, and system boundaries can substantially influence reported TEA and LCA outcomes. Furthermore, reliance on laboratory- and pilot-scale data for commercial-scale projections introduces uncertainty regarding culture stability, contamination control, equipment utilization, and long-term productivity. Future research should therefore prioritize pilot- and demonstration-scale validation supported by standardized TEA and LCA methodologies, transparent system boundaries, sensitivity analyses, and explicit uncertainty ranges. Continued development of high-productivity strains, low-energy harvesting and extraction technologies, efficient thermochemical conversion, microbiome-assisted cultivation, and integrated co-product recovery will be important for improving overall biorefinery performance. Ultimately, future marine microalgal biofuel development should move beyond single-product production toward integrated systems that evaluate fuel production, resource recovery, environmental performance, and co-product value simultaneously.

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Author Contributions

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