



**INTERNATIONAL JOURNAL OF
PHARMACEUTICAL SCIENCES**
[ISSN: 0975-4725; CODEN(USA): IJPS00]
Journal Homepage: <https://www.ijpsjournal.com>



Review Paper

Microalgae-Based Biodiesel as a Sustainable Renewable Energy Source: A Comprehensive Review

Shravani Jadhao*¹, Shivprasad Dhage²

¹Master of Science Department of Botony, Shri shivaji arts and science college chikhli, Maharashtra

²Assistant professor, department of Pharmacology, fergana Medical Institute of Public health Uzbekistan.

ARTICLE INFO

Published: 17 June 2026

Keywords:

microalgae; biodiesel;
transesterification; lipid
extraction; photobioreactor;
life cycle assessment;
biorefinery; renewable
energy

DOI:

10.5281/zenodo.20730674

ABSTRACT

The escalating global energy demand combined with increasing environmental deterioration caused by fossil fuel combustion has intensified the search for clean and renewable energy alternatives. Microalgae have emerged as a highly promising third-generation feedstock for biodiesel production owing to their exceptional lipid productivity, rapid growth rates, and ability to thrive on non-arable land using wastewater or saline water resources. [1] [2] This comprehensive review critically evaluates the current state of knowledge on microalgae-based biodiesel production, spanning cultivation technologies, harvesting methods, lipid extraction techniques, biodiesel synthesis, fuel characterization, and sustainability assessments. Several microalgae species, including *Chlorella vulgaris*, *Nannochloropsis oceanica*, and *Scenedesmus obliquus*, have demonstrated lipid contents ranging from 20% to 68% of their dry cell weight under optimized conditions. [3] [4] Closed photobioreactor systems offer superior biomass productivity compared with open raceway ponds, albeit at substantially higher capital costs. [5] Supercritical fluid extraction and wet lipid extraction approaches are gaining traction as energy-efficient alternatives to conventional solvent-based methods. [6] Life cycle assessments indicate that integrated biorefinery approaches, which valorize all biomass fractions, can substantially improve the overall energy balance and economic viability. [7] Advances in metabolic engineering, artificial intelligence-driven process optimization, and nanotechnology-assisted catalysis are expected to bridge the existing techno-economic gap. The integration of microalgae cultivation with carbon capture, wastewater treatment, and co-product valorization within circular bioeconomy frameworks represents the most promising pathway to commercial-scale sustainable biodiesel production

*Corresponding Author: Shravani Jadhao

Address: Master of Science Department of Botony, Shri shivaji arts and science college chikhli, Maharashtra..

Email ✉: jadhaoshravani95@gmail.com

Relevant conflicts of interest/financial disclosures: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.



INTRODUCTION

The twenty-first century is witnessing an unprecedented convergence of two existential challenges: the accelerating depletion of finite fossil fuel reserves and the worsening consequences of anthropogenic climate change. Global primary energy consumption has risen to approximately 580 EJ per year, with petroleum, coal, and natural gas collectively accounting for nearly 80% of this supply. [9] The combustion of these fuels releases approximately 36.8 Gt of carbon dioxide annually, contributing to atmospheric greenhouse gas concentrations that now exceed 420 ppm—a level unprecedented in at least 800,000 years of Earth history. [10] In this context, biofuels have attracted sustained scientific and policy interest as carbon-neutral, domestically producible alternatives to petroleum-derived transport fuels. Among the biofuel categories, biodiesel—a mixture of fatty acid methyl esters (FAME) produced through the transesterification of triacylglycerol-rich biomass with short-chain alcohols in the presence of a catalyst—offers particular advantages because it is compatible with existing diesel engines and distribution infrastructure with minimal modification. [11] [12] First-generation biodiesel derived from edible vegetable oils (soybean, rapeseed, palm) has faced criticism on account of its competition with food production and its indirect land-use change effects, which can partially or entirely negate its greenhouse gas savings. [13] Second-generation biodiesel from lignocellulosic residues or non-

edible oil crops avoids the food-versus-fuel conflict but is constrained by variable feedstock availability and expensive pretreatment processes. [14] Microalgae—unicellular or simple multicellular photosynthetic microorganisms distributed across diverse aquatic and terrestrial environments—have emerged as a compelling third-generation feedstock that overcomes many limitations of earlier generations. Their photosynthetic efficiency (3%–8%) exceeds that of terrestrial crops (0.5%–2%), and they can accumulate triacylglycerols amounting to 20%–68% of their dry cell weight under nitrogen-depleted conditions. [15] [16] Moreover, microalgae cultivation requires neither arable land nor freshwater when carried out with wastewater streams or marine water, and their rapid doubling times (as short as 3.5 hours in optimal conditions) enable continuous, year-round biomass harvesting. [17] Despite these compelling attributes, commercial-scale microalgae biodiesel remains economically uncompetitive with fossil diesel, primarily because of the high energy and capital expenditures associated with biomass cultivation, harvesting, and lipid extraction. [18] Bridging this techno-economic gap requires systematic advances across the entire production chain—from strain selection and cultivation engineering to downstream processing and integrated biorefinery design. This review provides a comprehensive, critically synthesized overview of the current state of knowledge and identifies the most productive directions for future research and development.

Figure 1. Comparative Overview: Microalgae vs. Conventional Biodiesel Feedstocks

Microalgae Advantages	Conventional Crop Limitations
<ul style="list-style-type: none"> • Oil yield: 10,000–50,000 L/ha/year <ul style="list-style-type: none"> • No arable land required • Rapid growth (doubling in hours) • CO₂ biofixation during growth <ul style="list-style-type: none"> • Can use wastewater nutrients • Year-round continuous production 	<ul style="list-style-type: none"> • Soybean: ~450 L/ha/year • Requires prime agricultural land <ul style="list-style-type: none"> • Seasonal harvest cycles • Food vs. fuel competition <ul style="list-style-type: none"> • High freshwater demand • Indirect land-use change emissions



- Non-food competitive feedstock

- Lower photosynthetic efficiency

Figure 1. Schematic comparison of microalgae-based and conventional crop-based biodiesel feedstocks highlighting key productivity and sustainability parameters.

2. Microalgae as a Biodiesel Feedstock

2.1 Types of Microalgae Used for Biodiesel Production

The kingdom of microalgae encompasses an estimated 200,000–800,000 species belonging to diverse taxonomic groups, of which only a fraction have been evaluated for biofuel potential. The most extensively studied genera for biodiesel applications belong to the divisions Chlorophyta (green algae), Bacillariophyta (diatoms), Cyanobacteria, and Eustigmatophyta. [19] [20] *Chlorella vulgaris* is among the most widely investigated species owing to its robust growth, tolerance to contamination, and lipid contents that

can exceed 56% on a dry weight basis under nitrogen starvation. [21] *Nannochloropsis oceanica* is valued for its high eicosapentaenoic acid (EPA) content and lipid productivity exceeding 300 mg/L/day under optimized conditions. [22] *Scenedesmus obliquus* and *Scenedesmus dimorphus* have demonstrated lipid contents ranging from 16% to 40%, with fatty acid profiles dominated by C16–C18 chains suitable for FAME production. [23] *Botryococcus braunii* is noteworthy for its production of long-chain hydrocarbons (botryococcenes) that can be directly refined into drop-in transport fuels, though its slow growth rate restricts industrial applicability. [24] Marine species such as *Isochrysis galbana* and *Dunaliella salina* offer the advantage of cultivation in seawater, reducing competition for freshwater resources. [25]

Table 1. Lipid Content and Productivity of Key Microalgae Species for Biodiesel Production

Species	Lipid Content (% DW)	Lipid Productivity (mg/L/day)
<i>Chlorella vulgaris</i>	28–56	11.2–178
<i>Nannochloropsis oceanica</i>	31–68	84–310
<i>Scenedesmus obliquus</i>	16–40	11.1–53
<i>Botryococcus braunii</i>	25–75	3–5.5
<i>Dunaliella salina</i>	6–25	12–34
<i>Isochrysis galbana</i>	20–33	37.8–57.8
<i>Phaeodactylum tricornutum</i>	20–30	44.8–67.2
<i>Haematococcus pluvialis</i>	25–35	10.3–22.7

Table 1. Summary of lipid content and volumetric lipid productivity for the most studied microalgae species under optimal growth conditions. DW: dry weight. Data compiled from [3,4,21–25].

2.2 Growth Characteristics

Microalgae growth follows classical phases—lag, exponential, linear, declining, and stationary—governed by the interplay of light availability, temperature, nutrient supply, CO₂ concentration, and pH. [26] Under photoautotrophic conditions, biomass productivity is primarily limited by light



penetration, which decreases exponentially with culture depth due to cell self-shading. Maximum specific growth rates for common biodiesel-relevant species range from 0.17 to 2.5 day⁻¹. [27] Heterotrophic cultivation, in which organic carbon sources (glucose, acetate, glycerol) substitute for light-driven CO₂ fixation, can yield substantially higher biomass and lipid concentrations but requires sterile conditions and organic carbon inputs that add to production costs. [28] Mixotrophic cultivation—combining light-driven photosynthesis with organic carbon assimilation—has been demonstrated to improve biomass productivity by 2–5-fold compared with strict photoautotrophy in several species. [29]

2.3 Lipid Productivity and Composition

For biodiesel production, the critical parameter is not total lipid content alone but volumetric lipid productivity (mg lipid L⁻¹ day⁻¹), which integrates biomass concentration and growth rate. A species with 30% lipid content but a growth rate of 2 g/L/day may outperform a species with 60% lipid content growing at only 0.3 g/L/day. [30]

Microalgal lipids destined for biodiesel production are primarily neutral lipids, especially triacylglycerols (TAGs), which accumulate in cytoplasmic lipid droplets under nutrient stress, particularly nitrogen, phosphorus, or sulfur limitation. [31] The fatty acid profile of TAGs is dominated by C16 and C18 chains (palmitic, stearic, oleic, linoleic, and linolenic acids) in most green algae, yielding FAME mixtures with biodiesel properties comparable to those of soybean or rapeseed FAME. [32]

2.4 Comparison with Terrestrial Oil Crops

A widely cited analysis by Chisti (2007) estimated that microalgae can yield 58,700–136,900 L of biodiesel per hectare per year, compared with 446 L/ha/year for soybean, 1,190 L/ha/year for rapeseed, and 5,950 L/ha/year for palm oil—the

highest-yielding terrestrial crop. [33] These projections assume photobioreactor cultivation; open-pond systems yield approximately 10,000–25,000 L/ha/year, still 5–20-fold higher than palm oil. [34]

Beyond productivity, microalgae offer additional sustainability advantages: their cultivation does not require herbicides or pesticides, they can utilize flue gas CO₂ directly, and their residual biomass after oil extraction retains high protein content suitable for animal feed or anaerobic digestion, enabling biorefinery integration. [35]

3. Cultivation Technologies

3.1 Open Pond Systems

Open raceway ponds (ORPs) are the most mature and widely deployed microalgae cultivation technology, representing the majority of currently operating commercial-scale facilities. [36] A typical ORP consists of a shallow (20–30 cm depth) oval channel through which culture medium is circulated by paddle wheels at 0.2–0.3 m/s to prevent cell settling and ensure adequate light exposure and CO₂ distribution. Capital costs for ORPs are substantially lower than those for photobioreactors, typically USD 100,000–300,000 per hectare. [37] However, ORPs suffer from several fundamental limitations: high evaporative water losses, poor temperature control, susceptibility to contamination by competing organisms, limited control over light distribution, and restricted CO₂ utilization efficiency (10%–30%). [38] Areal biomass productivities in ORPs typically range from 10–25 g/m²/day, substantially below the theoretical maximum of approximately 60 g/m²/day estimated for idealized solar conditions. [39]

3.2 Photobioreactors

Closed photobioreactors (PBRs) address many limitations of open systems by providing a controlled, contamination-resistant environment.



The principal PBR configurations include tubular (horizontal or helical), flat-panel, and column (bubble column or airlift) designs. [40]

Tubular PBRs, consisting of transparent tubes (20–60 mm diameter) through which culture is recirculated, have been scaled to volumes of several hundred cubic meters and achieve biomass

productivities of 20–40 g/m²/day—typically 2–4-fold higher than ORPs. [41] Flat-panel PBRs offer minimal light path lengths (2–10 cm), enabling high biomass concentrations and are particularly suited to high-value products, though their scale-up is limited by structural constraints and cleaning difficulties. [42]

Table 2. Performance Comparison of Microalgae Cultivation Systems

Parameter	Open Raceway Pond	Closed Photobioreactor
Capital cost (USD/m ³)	50–200	1,000–10,000
Biomass productivity (g/m ² /day)	10–25	20–40
Contamination risk	High	Low
CO ₂ utilization efficiency	10–30%	70–95%
Water evaporation	High	Negligible
Temperature control	Difficult	Feasible
Scale-up ease	High	Moderate–Difficult
Operating cost	Low	High

Table 2. Comparative performance metrics for open raceway ponds and closed photobioreactor cultivation systems. Data compiled from [36–42].

3.3 Hybrid Cultivation Systems

Hybrid systems that combine the advantages of open and closed configurations have been developed to optimize both cost and productivity. [43] A widely adopted two-stage strategy employs a PBR for inoculum production and initial biomass accumulation under controlled, nitrogen-sufficient conditions to maximize cell density, followed by transfer to an ORP for a nitrogen-starvation stage that triggers lipid accumulation. This approach decouples the growth phase from the lipid induction phase, enabling independent optimization of each step. [44]

3.4 Factors Affecting Biomass Production

Light intensity and photoperiod are primary determinants of microalgae growth in

photoautotrophic systems. The compensation irradiance—the light level at which photosynthesis equals respiration—is typically 10–30 μmol photons/m²/s, while saturation irradiance ranges from 200 to 500 μmol/m²/s depending on species and adaptation state. [45] At irradiances above saturation, photoinhibition occurs, reducing photosynthetic efficiency. Optimal growth temperatures range from 20°C to 35°C for most biodiesel-relevant species, with productivity declining sharply below 15°C and above 40°C. [46] CO₂ concentration in the range of 2%–5% (v/v) typically maximizes photosynthetic activity and biomass production, while the optimal pH for most green algae lies between 7.0 and 8.0, maintained in part by CO₂ dissolution dynamics. [47]

4. Harvesting and Dewatering Methods

Microalgae harvesting represents one of the most significant cost and energy barriers in the



production chain, accounting for 20%–30% of total production costs. [48] The challenge arises from the dilute nature of microalgae cultures (0.5–5 g/L in open ponds; 2–10 g/L in PBRs), the small cell size (2–20 μm for most species), and the negative surface charge that promotes colloidal stability. Efficient harvesting requires concentrating the biomass by a factor of 100–1000 to achieve paste-like slurries of 100–400 g/L. [49]

4.1 Flocculation

Flocculation destabilizes the negatively charged colloidal suspension of microalgae cells, promoting aggregation into larger particles that settle under gravity. Chemical flocculants, including aluminum sulfate (alum), ferric chloride, and synthetic polyelectrolytes such as polyacrylamide, are effective at concentrations of 50–200 mg/L but introduce metal contamination and generate chemical sludge. [50] Bioflocculation—induced by pH increase (pH > 10) through CO₂ stripping or NaOH addition—is a cost-effective alternative that avoids chemical contamination. [51] Autoflocculation of certain species under CO₂ limitation and natural bioflocculation induced by bacterial consortia in mixed cultures represent promising low-energy, low-cost harvesting approaches suitable for large-scale operations. [52]

4.2 Centrifugation

Centrifugation is the most reliable and widely used harvesting technique for high-value microalgae

products, achieving concentration factors of 300–1000 and harvesting efficiencies above 95%. [53] However, its high energy consumption (0.1–2 kWh/kg biomass) and capital cost limit its applicability in large-scale commodity biodiesel production. Disc-stack centrifuges operating at 4,000–14,000 $\times g$ are most commonly employed at commercial scale. [54]

4.3 Filtration

Membrane filtration—including microfiltration (0.1–10 μm pore size) and ultrafiltration—can achieve efficient biomass recovery with lower energy consumption than centrifugation (0.3–1.4 kWh/m³) but is susceptible to membrane fouling, particularly with small cells or extracellular polymeric substances. [55] Vacuum belt filtration and pressure filtration are used as secondary dewatering steps following flocculation or gravity sedimentation. [56]

4.4 Emerging Harvesting Technologies

Electrocoagulation applies an electric current to aluminum or iron sacrificial electrodes that release metal cations in situ, inducing flocculation without chemical addition. Energy consumption of 0.06–2.0 kWh/m³ and harvesting efficiencies of 80%–99% have been reported. [57] Dissolved air flotation (DAF) is widely used in wastewater treatment and has been adapted for microalgae harvesting, with flotation efficiencies of 80%–90% achievable following pre-flocculation. [58]

Figure 2. Typical Microalgae Harvesting and Dewatering Process Chain

Step 1	Primary Settling / Flocculation	Culture pH adjustment or chemical addition; cell aggregation into flocs; sedimentation in lamella settlers. Energy: 0.01–0.1 kWh/m ³ .
Step 2	Secondary Concentration	Dissolved air flotation or membrane filtration to achieve 2%–10% total suspended solids (TSS). Energy: 0.1–0.5 kWh/m ³ .
Step 3	Tertiary Dewatering	Centrifugation or filter press to reach 15%–25% TSS paste. Energy: 0.5–2 kWh/kg biomass.

Step 4	Drying (optional)	Spray drying, drum drying, or solar drying to < 10% moisture for solvent extraction. Energy: 1–5 kWh/kg biomass.
--------	-------------------	--

Figure 2. Sequential process chain for microalgae harvesting and dewatering, with typical energy inputs at each stage. TSS: total suspended solids.

5. Lipid Extraction Techniques

Efficient lipid extraction from harvested microalgae biomass is a critical processing step that profoundly affects both the yield of oil recovered and the total energy balance of biodiesel production. The selection of an extraction method must balance oil recovery efficiency, cell disruption effectiveness, energy consumption, solvent recyclability, and scalability. [59]

5.1 Mechanical Methods

Bead milling and high-pressure homogenization are the principal mechanical cell disruption methods evaluated at pilot scale. Bead milling passes the slurry through a grinding chamber packed with glass or ceramic beads (0.3–1.5 mm), generating shear forces that rupture cell walls. Cell disruption efficiencies of 80%–99% are achievable at energy inputs of 1–10 kWh/kg dry biomass. [60] Ultrasonication exploits cavitation—the formation and collapse of microbubbles generated by high-frequency pressure waves (20–40 kHz)—to disrupt cell membranes. While effective at laboratory scale with lipid extraction enhancements of 30%–60%, scale-up of ultrasonication equipment remains challenging and energy-intensive. [61]

5.2 Solvent Extraction

The Bligh and Dyer method (chloroform:methanol:water, 1:2:0.8 v/v) and the Folch method (chloroform:methanol, 2:1 v/v) are the gold standards for laboratory-scale total lipid extraction, achieving recoveries of 95%–100%. [62] However, the acute toxicity and

environmental persistence of chlorinated solvents prohibit their use at industrial scale. Hexane, approved as a food-grade solvent, is widely used industrially but is only effective on dried biomass and recovers primarily non-polar neutral lipids. [63]

5.3 Supercritical Fluid Extraction

Supercritical CO₂ (SC-CO₂) extraction operates above the critical point of CO₂ (31.1°C, 73.8 bar), at which the fluid exhibits liquid-like solvating power combined with gas-like diffusivity. SC-CO₂ is selective for neutral lipids (TAGs), non-toxic, and leaves no solvent residues in the extracted oil or spent biomass. [64] Lipid extraction efficiencies of 80%–98% have been reported for dry microalgae with moderate addition of a co-solvent (ethanol or methanol) to enhance polar lipid recovery. [65] The principal limitation is high capital cost and energy consumption, as pressurizing CO₂ to 200–400 bar requires approximately 0.5–1.5 kWh/kg extracted oil. [66]

5.4 Green Extraction Approaches

Wet lipid extraction—processing biomass with high water content (80%–90%) without prior drying—can substantially reduce the total process energy demand by eliminating the energy-intensive drying step. [67] Hydrothermal liquefaction (HTL) converts wet biomass (water content up to 80%) into bio-crude oil, gas, aqueous phase, and solid residue at temperatures of 280–370°C and pressures of 10–25 MPa, achieving oil yields of 25%–50% from total biomass dry weight. [68] Ionic liquid-assisted extraction, enzymatic cell disruption, and microwave-assisted extraction have all demonstrated improved lipid recovery and reduced solvent consumption at laboratory scale;

however, their economic and environmental footprints at commercial scale require further investigation. [69]

6. Biodiesel Production Processes

6.1 Transesterification Reaction

Biodiesel is produced through transesterification—the reaction of triacylglycerols (TAGs) with a short-chain alcohol (typically methanol) in the presence of a catalyst to yield fatty acid methyl esters (FAME) and glycerol as a by-product. [70] The stoichiometry requires 3 mol of methanol per mole of TAG; in practice, a methanol:oil molar ratio of 6:1 is commonly employed to drive the equilibrium toward FAME formation. [71] The overall transesterification pathway proceeds through two sequential intermediate steps: TAGs are first converted to diacylglycerols (DAGs), then to monoacylglycerols (MAGs), and finally to glycerol, with one molecule of FAME liberated at each step. Under optimized homogeneous alkaline catalysis, FAME conversion efficiencies of 96%–99% are routinely achieved. [72]

6.2 Catalysts Used in Biodiesel Synthesis

Homogeneous base catalysts, particularly sodium hydroxide (NaOH) and potassium hydroxide (KOH) at concentrations of 0.5%–2% (w/w oil), are preferred industrially because of their high activity and low cost, enabling reaction completion within 30–90 minutes at 55–65°C. [73] However, homogeneous base catalysis is incompatible with feedstocks containing more

than 1%–3% free fatty acids (FFAs), which cause soap formation and phase separation. Microalgal oils extracted under non-optimized conditions can have FFA contents of 5%–20%, necessitating either acid pre-esterification or the use of acid catalysts. [74] Heterogeneous solid catalysts—including metal oxides (CaO, MgO, TiO₂), zeolites, and hydrotalcites—offer the advantages of easy product separation, catalyst recyclability, and tolerance to FFAs and water. [75] Enzymatic transesterification using immobilized lipases (particularly *Candida antarctica* lipase B) operates at mild temperatures (30–40°C), exhibits high specificity, tolerates FFAs and water, and produces glycerol of higher purity than chemical processes, though enzyme cost and susceptibility to methanol inhibition remain barriers. [76]

6.3 Process Optimization Strategies

In situ transesterification—directly converting lipids in dried or wet microalgae biomass without a prior extraction step—has been extensively investigated as a process-intensification strategy. By eliminating the extraction unit operation, in situ transesterification can reduce solvent consumption and processing steps, though biomass drying remains an energy-intensive prerequisite in most implementations. [77] Response surface methodology (RSM) and the Box–Behnken or central composite design experimental frameworks have been widely applied to optimize transesterification parameters (methanol:oil ratio, catalyst concentration, temperature, reaction time) and have demonstrated FAME yields of 90%–98% under optimized conditions for microalgae-derived oils. [78]

Figure 3. Integrated Microalgae Biodiesel Production Process Flow

Step 1	Microalgae Cultivation	Photoautotrophic growth in open ponds or photobioreactors; CO ₂ and nutrient supply; biomass concentration 0.5–5 g/L.
Step 2	Harvesting & Dewatering	Flocculation → centrifugation; biomass concentration increased to 100–400 g/L paste.



Step 3	Drying	Spray or drum drying to < 5% moisture content for solvent extraction (optional for wet processes).
Step 4	Lipid Extraction	Solvent (hexane), SC-CO ₂ , or wet extraction; oil yield 20–60% of dry biomass.
Step 5	Transesterification	Reaction with methanol (6:1 molar ratio) and catalyst (NaOH 1%); 60°C, 60 min; FAME conversion > 96%.
Step 6	Separation & Purification	Phase separation of FAME and glycerol; water washing; vacuum distillation; biodiesel purity > 99%.
Step 7	Co-product Valorization	Glycerol → biochemicals; spent biomass → biogas (anaerobic digestion) or animal feed.

Figure 3. Integrated process flow diagram for microalgae-based biodiesel production from cultivation to fuel-grade FAME, with co-product valorization pathways.

7. Biodiesel Characterization and Fuel Properties

7.1 Physicochemical Properties

Table 3. Fuel Properties of Microalgae Biodiesel vs. Petrodiesel and ASTM/EN Standards

Property	Microalgae FAME	Petrodiesel / Standard
Kinematic viscosity (mm ² /s, 40°C)	3.5–5.5	2.0–4.5 (ASTM D975)
Cetane number	45–67	> 47 (ASTM D6751)
Flash point (°C)	130–180	> 93 (ASTM D6751)
Cloud point (°C)	–5 to +10	Varies by grade
Calorific value (MJ/kg)	37.0–41.5	42–45 (petrodiesel)
Iodine value (g I ₂ /100 g)	50–180	< 120 (EN 14214)
Acid value (mg KOH/g)	< 0.5	< 0.5 (ASTM D6751)
Water content (mg/kg)	< 500	< 500 (EN 14214)

Table 3. Comparative fuel property data for microalgae-derived FAME relative to petrodiesel specifications and ASTM D6751/EN 14214 biodiesel standards. Data from [79,80].

7.2 Fuel Standards

The fuel quality of microalgae-derived biodiesel is governed primarily by the fatty acid composition of the feedstock oil. Key performance-determining parameters include kinematic viscosity, cetane number, cloud and pour points, oxidation stability, calorific value, and iodine value. [79]

Microalgae biodiesel must conform to ASTM D6751 (United States) or EN 14214 (European Union) standards to qualify for blending with fossil diesel or standalone use. The most challenging parameters for microalgal FAME are oxidation stability (minimum 3 h induction period



under EN 14112 Rancimat method) and cold-flow properties. [80] The high polyunsaturated fatty acid (PUFA) content of certain microalgae species—particularly EPA (C20:5) and DHA (C22:6) in marine species—can cause FAME with iodine values above the EN 14214 maximum of 120 g I₂/100 g and poor oxidation stability. Blending with more saturated feedstocks, antioxidant addition, or genetic engineering to shift fatty acid profiles toward C18:1 (oleic acid) are strategies to address this limitation. [81]

7.3 Engine Performance and Emissions

Engine performance tests of microalgae biodiesel blends (B5–B100) have demonstrated brake thermal efficiencies within 2%–5% of neat petrodiesel for blends up to B20, with a slight increase in brake-specific fuel consumption due to the lower calorific value of FAME. [82] Microalgae biodiesel combustion produces measurably lower particulate matter (PM) emissions (20%–50% reduction for B100), reduced hydrocarbon (HC) emissions, and lower carbon monoxide (CO) compared with petrodiesel, attributable to the oxygen content of FAME promoting more complete combustion. [83] Nitrogen oxide (NO_x) emissions from biodiesel combustion are subject to a slight increase (2%–10%) compared with petrodiesel under most operating conditions, attributed to higher adiabatic flame temperatures. This increase can be mitigated by fuel injection timing retardation or antioxidant additives. [84]

8. Environmental and Economic Assessment

8.1 Life Cycle Assessment (LCA)

Life cycle assessment (LCA) provides a systems-level accounting of the environmental impacts of microalgae biodiesel production from cradle to grave, encompassing resource extraction, cultivation, processing, fuel use, and waste

disposal. [85] The functional unit most commonly employed in microalgae LCA studies is 1 MJ of energy delivered to the vehicle powertrain or 1 tonne of FAME produced. [86]

LCA results for microalgae biodiesel vary widely across studies, reflecting differences in cultivation system (ORP vs. PBR), geographical location, energy grid carbon intensity, and system boundaries. [87] For open-pond systems with wastewater nutrient supply and anaerobic digestion of spent biomass, global warming potential (GWP) values of 15–50 g CO₂-eq/MJ have been reported, representing a 40%–85% reduction compared with fossil diesel (83 g CO₂-eq/MJ). Conversely, PBR systems without co-product credits may have GWP values exceeding that of fossil diesel due to the high energy demand of reactor operation. [88]

8.2 Carbon Footprint

The carbon footprint of microalgae-based biodiesel is highly sensitive to the source of CO₂ supplied to the culture. When industrial flue gas (15%–20% CO₂) from power plants or cement factories is utilized, direct CO₂ mitigation credits can substantially improve the carbon balance. [89] Microalgae fix approximately 1.83 kg CO₂ per kg of dry biomass produced, implying that a facility producing 100 tonnes of dry biomass per day sequesters approximately 183 tonnes of CO₂ per day, though this carbon is re-released upon combustion of the biodiesel produced. [90]

8.3 Techno-Economic Analysis

Techno-economic analyses (TEA) consistently indicate that microalgae biodiesel production costs substantially exceed those of fossil diesel and crop-based biodiesel. Production cost estimates for open-pond systems range from USD 2.50 to USD 8.00 per liter of FAME, compared with a fossil diesel price of approximately USD 0.8–1.2 per liter. [91]



Table 4. Key Cost Contributors in Microalgae Biodiesel Production (Open Pond System)

Cost Component	Share of Total Cost (%)	Reduction Strategy
Biomass cultivation	40–55	Wastewater nutrient use; CO ₂ flue gas
Harvesting & dewatering	20–30	Bioflocculation; improved membranes
Lipid extraction & drying	10–15	Wet extraction; solar drying
Transesterification	5–10	Heterogeneous catalysis; in situ TESE
Capital annualization	15–25	Scale-up; modular construction
Co-product credits	–15 to –30	Biorefinery approach; protein sale

Table 4. Breakdown of production cost contributors for microalgae biodiesel from open-pond systems, with potential reduction strategies. Data compiled from TEA studies [91,92].

The breakeven production cost is sensitive to the price credited for co-products. When protein-rich spent biomass is sold as animal feed (USD 300–500/tonne), glycerol is refined for pharmaceutical or cosmetic use, and biogas from anaerobic digestion offsets process energy, integrated biorefinery models project production costs of USD 3.5–5.0/L, potentially declining to USD 1.5–2.5/L with further technological maturation. [92]

9. Challenges and Limitations

9.1 High Production Cost

The overarching challenge confronting microalgae biodiesel commercialization is economic uncompetitiveness with fossil fuels at the current state of technology. [93] The production cost gap—approximately 3–8-fold depending on assumptions—is attributable to a constellation of interconnected technical and economic factors that require simultaneous improvement across multiple process stages rather than breakthrough advances in any single area.

9.2 Scale-Up Issues

The transition from laboratory demonstration to pilot scale to commercial production is accompanied by fundamental challenges including the maintenance of sterility in large open systems, uniform light distribution and CO₂ supply in scaled PBRs, and the reliable operation of downstream processing equipment at high throughput. [94] Most published productivity data derive from laboratory or small pilot facilities (< 100 m³ culture volume), and substantial productivity losses have been documented during scale-up, partly attributable to increased self-shading, reduced mixing uniformity, and contamination pressure. [95]

9.3 Energy Requirements

The net energy ratio (NER)—the ratio of energy contained in the biodiesel produced to the total fossil energy consumed in production—must exceed 1.0 for a biofuel to represent a net energy gain. For microalgae biodiesel, NER values range from below 1.0 (energy-negative) for PBR systems without co-product recovery to approximately 1.5–3.0 for optimized open-pond systems with full biorefinery integration. [96] The most energy-intensive individual steps are biomass drying and centrifugation, which together



can account for 50%–70% of total process energy input. [97]

9.4 Commercialization Barriers

Beyond technical and economic challenges, the commercialization of microalgae biodiesel faces regulatory, market, and policy barriers. Existing biofuel support policies in major markets (EU Renewable Energy Directive, US Renewable Fuel

Standard) have been slow to establish specific, favorable provisions for third-generation algal biofuels. [98] The absence of standardized cultivation, harvesting, and processing protocols complicates quality consistency, investor confidence, and regulatory approval. Supply chain development for large-scale CO₂, nutrient, and water inputs must be established concurrently with production scale-up. [99]

Figure 4. Key Challenges and Corresponding Mitigation Strategies

Challenge	Mitigation Strategy
<ul style="list-style-type: none"> • High cultivation cost (nutrients, CO₂) • High harvesting energy (centrifugation) <ul style="list-style-type: none"> • Drying energy demand • Low FAME conversion (high FFA oil) <ul style="list-style-type: none"> • Poor oxidation stability (PUFAs) <ul style="list-style-type: none"> • Scale-up productivity loss • Contamination in open systems 	<ul style="list-style-type: none"> • Wastewater + flue gas CO₂ integration • Bioflocculation + gravity sedimentation <ul style="list-style-type: none"> • Wet lipid extraction / HTL • Acid pre-esterification or enzymatic catalysis • Genetic strain engineering (↑ oleic acid) <ul style="list-style-type: none"> • Modular hybrid ORP-PBR systems • Polyculture design + monitoring AI

Figure 4. Summary of principal technical and economic challenges in microalgae biodiesel production with corresponding mitigation strategies identified in recent literature.

10. Future Perspectives

10.1 Genetic Engineering of Microalgae

Advances in synthetic biology, CRISPR-Cas9 genome editing, and metabolic flux analysis are enabling unprecedented precision in engineering microalgae lipid metabolism. [100] Key metabolic engineering targets include overexpression of acetyl-CoA carboxylase (ACCase) and diacylglycerol acyltransferase (DGAT)—rate-limiting enzymes in TAG biosynthesis—and knockdown of lipid catabolism pathways. [101] Nitrogen-sensing regulatory pathways controlling the growth-to-lipid-accumulation transition have been characterized, opening possibilities for decoupling lipid induction from growth arrest. [102]

10.2 Artificial Intelligence Applications

Machine learning and artificial intelligence algorithms are increasingly applied to optimize microalgae cultivation and processing. Convolutional neural networks (CNNs) have been employed for real-time image-based monitoring of culture health, contamination detection, and cell density estimation, enabling autonomous process control. [103] Deep learning models trained on multi-dimensional datasets integrating light intensity, temperature, nutrient concentrations, and growth rate data have demonstrated predictive accuracy for biomass productivity of ±5%–10%, enabling proactive process adjustments that improve productivity by 15%–25% compared with conventional PID control. [104]

10.3 Nanotechnology-Assisted Production

Nanocatalysts, nanoparticle-enhanced light harvesting, and nano-enabled cell disruption represent emerging nanotechnology applications in the microalgae biodiesel value chain. [105] Magnetic nano-biocatalysts—lipase immobilized on iron oxide nanoparticles—combine the substrate tolerance of enzymatic catalysis with



magnetic recovery by an external field, enabling efficient catalyst reuse over 10–20 cycles with retention of > 80% activity. [106] Carbon quantum dots and plasmonic gold nanoparticles incorporated into PBR walls have been demonstrated to enhance light harvesting efficiency by 15%–30% through photoluminescence re-emission at wavelengths optimal for algal photosynthesis. [107]

10.4 Integrated Biorefinery Concepts

The biorefinery concept—analogue to petroleum refinery fractionation—envision microalgae as a platform feedstock for simultaneous production of biodiesel (from TAGs), omega-3 fatty acids (EPA, DHA), astaxanthin or other carotenoids, phycocyanin pigments, biohydrogen, biogas, bioplastics, and fertilizers, with each product stream derived from successive biomass fractionation steps. [108] Techno-economic models demonstrate that biorefineries targeting simultaneous recovery of astaxanthin (USD 2,000–10,000/kg), EPA (USD 150–400/kg), and biodiesel are substantially more economically viable than single-product biodiesel facilities. [109] Integration with municipal wastewater treatment generates additional revenue through nutrient removal services (nitrogen, phosphorus), while coupling with CO₂-emitting industries (power plants, cement) provides low-cost carbon supply and carbon credits under emerging carbon pricing frameworks. [110]

CONCLUSION

This comprehensive review has examined the multifaceted scientific, technological, economic, and environmental dimensions of microalgae-based biodiesel production. The synthesis of evidence across more than seven decades of research reveals both the extraordinary promise of microalgae as a renewable energy feedstock and the persistent barriers that have, thus far, prevented

commercial-scale viability at competitive economics. From a biological perspective, the exceptional diversity of microalgae species—with lipid contents spanning 6%–75% of dry cell weight and volumetric productivities up to 310 mg/L/day in optimized systems—provides ample genetic raw material for strain selection and improvement. The advent of CRISPR-Cas9 and other precision genome editing tools is beginning to translate mechanistic understanding of lipid metabolism into engineered strains with simultaneously improved growth rate, lipid accumulation, and fatty acid profile. From a process engineering perspective, hybrid cultivation systems, wet lipid extraction, in situ transesterification, and heterogeneous nanocatalysis are collectively reducing the energy intensity and capital requirements of each production step. The integration of microalgae cultivation with wastewater treatment and industrial CO₂ utilization provides both nutrient cost reduction and additional environmental service revenues that strengthen the overall economic case. Life cycle and techno-economic analyses consistently demonstrate that integrated biorefinery configurations—maximizing value extraction from all biomass components—are far more economically and environmentally favorable than dedicated biodiesel production. Under optimistic but realistic scenarios combining advanced strains, open-pond cultivation with wastewater-derived nutrients, wet extraction, and multi-product recovery, production costs of USD 1.5–2.5/L may be achievable within a 10–15 year development horizon. Key priorities for future research include: (1) development of robust, high-lipid strains through precision metabolic engineering; (2) demonstration of pilot-to-commercial scale-up with documented productivity retention; (3) standardization of LCA methodology and system boundaries to enable meaningful cross-study comparisons; (4)

development of integrated co-culture or polyculture systems that exploit ecological interactions for productivity and contamination resistance; and (5) exploration of AI-driven autonomous control systems for real-time process optimization across the entire value chain. The transition to a sustainable energy future requires a portfolio of renewable solutions. Microalgae-based biodiesel, particularly within the context of circular bioeconomy and integrated biorefinery frameworks, holds genuine promise as a component of this portfolio—not as a panacea, but as a valuable contributor to decarbonizing hard-to-electrify transport sectors while delivering co-benefits in wastewater treatment, carbon capture, and high-value biochemical production.

REFERENCES

1. Chisti, Y. Biodiesel from microalgae. *Biotechnology Advances* 2007, 25(3), 294–306.
2. Hu, Q.; Sommerfeld, M.; Jarvis, E.; Ghirardi, M.; Posewitz, M.; Seibert, M.; Darzins, A. Microalgal triacylglycerols as feedstocks for biofuel production: perspectives and advances. *Plant Journal* 2008, 54(4), 621–639.
3. Spolaore, P.; Joannis-Cassan, C.; Duran, E.; Isambert, A. Commercial applications of microalgae. *Journal of Bioscience and Bioengineering* 2006, 101(2), 87–96.
4. Mata, T.M.; Martins, A.A.; Caetano, N.S. Microalgae for biodiesel production and other applications: A review. *Renewable and Sustainable Energy Reviews* 2010, 14(1), 217–232.
5. Brennan, L.; Owende, P. Biofuels from microalgae—A review of technologies for production, processing, and extractions of biofuels and co-products. *Renewable and Sustainable Energy Reviews* 2010, 14(2), 557–577.
6. Halim, R.; Harun, R.; Danquah, M.K.; Webley, P.A. Microalgal cell disruption for biofuel development. *Applied Energy* 2012, 91(1), 116–121.
7. Collet, P.; Helias, A.; Lardon, L.; Ras, M.; Goy, R.A.; Steyer, J.P. Life-cycle assessment of microalgae culture coupled to biogas production. *Bioresource Technology* 2011, 102(1), 207–214.
8. Lam, M.K.; Lee, K.T. Microalgae biofuels: A critical review of issues, problems and the way forward. *Biotechnology Advances* 2012, 30(3), 673–690.
9. IEA. *World Energy Outlook 2023*; International Energy Agency: Paris, France, 2023.
10. IPCC. *Climate Change 2023: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report*; Cambridge University Press: Cambridge, UK, 2023.
11. Demirbas, A. Progress and recent trends in biodiesel fuels. *Energy Conversion and Management* 2009, 50(1), 14–34.
12. Graboski, M.S.; McCormick, R.L. Combustion of fat and vegetable oil derived fuels in diesel engines. *Progress in Energy and Combustion Science* 1998, 24(2), 125–164.
13. Searchinger, T.; Heimlich, R.; Houghton, R.A.; Dong, F.; Elobeid, A.; Fabiosa, J.; Tokgoz, S.; Hayes, D.; Yu, T.H. Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science* 2008, 319(5867), 1238–1240.
14. Sims, R.E.H.; Mabee, W.; Saddler, J.N.; Taylor, M. An overview of second generation biofuel technologies. *Bioresource Technology* 2010, 101(6), 1570–1580.
15. Williams, P.J.L.B.; Laurens, L.M.L. Microalgae as biodiesel & biomass feedstocks: Review & analysis of the



- biochemistry, energetics & economics. *Energy & Environmental Science* 2010, 3(5), 554–590.
16. Sheehan, J.; Dunahay, T.; Benemann, J.; Roessler, P. A Look Back at the U.S. Department of Energy's Aquatic Species Program: Biodiesel from Algae; National Renewable Energy Laboratory: Golden, CO, USA, 1998.
 17. Pulz, O.; Gross, W. Valuable products from biotechnology of microalgae. *Applied Microbiology and Biotechnology* 2004, 65(6), 635–648.
 18. Pienkos, P.T.; Darzins, A. The promise and challenges of microalgal-derived biofuels. *Biofuels, Bioproducts and Biorefining* 2009, 3(4), 431–440.
 19. Guiry, M.D. How many species of algae are there? *Journal of Phycology* 2012, 48(5), 1057–1063.
 20. Borowitzka, M.A. High-value products from microalgae—their development and commercialisation. *Journal of Applied Phycology* 2013, 25(3), 743–756.
 21. Converti, A.; Casazza, A.A.; Ortiz, E.Y.; Perego, P.; Del Borghi, M. Effect of temperature and nitrogen concentration on the growth and lipid content of *Nannochloropsis oculata* and *Chlorella vulgaris* for biodiesel production. *Chemical Engineering and Processing* 2009, 48(6), 1146–1151.
 22. Simionato, D.; Basso, S.; Giacometti, G.M.; Morosinotto, T. Optimization of light use efficiency for biofuel production in green algae. *Biophysical Chemistry* 2013, 182, 71–78.
 23. Mandal, S.; Mallick, N. Microalga *Scenedesmus obliquus* as a potential source for biodiesel production. *Applied Microbiology and Biotechnology* 2009, 84(2), 281–291.
 24. Metzger, P.; Largeau, C. *Botryococcus braunii*: a rich source for hydrocarbons and related ether lipids. *Applied Microbiology and Biotechnology* 2005, 66(5), 486–496.
 25. Moheimani, N.R.; Borowitzka, M.A. The long-term culture of the coccolithophore *Pleurochrysis carterae* (Haptophyta) in outdoor raceway ponds. *Journal of Applied Phycology* 2006, 18(6), 703–712.
 26. Richmond, A. *Handbook of Microalgal Culture: Biotechnology and Applied Phycology*; Blackwell Science: Oxford, UK, 2004.
 27. Sforza, E.; Cipriani, R.; Morosinotto, T.; Bertucco, A.; Giacometti, G.M. Excess CO₂ supply inhibits mixotrophic growth of *Chlorella protothecoides* and *Nannochloropsis salina*. *Bioresource Technology* 2012, 104, 523–529.
 28. Chen, F. High cell density culture of microalgae in heterotrophic growth. *Trends in Biotechnology* 1996, 14(11), 421–426.
 29. Chojnacka, K.; Marquez-Rocha, F.J. Kinetic and stoichiometric relationships of the energy and carbon metabolism in the culture of microalgae. *Biotechnology* 2004, 3(1), 21–34.
 30. Griffiths, M.J.; Harrison, S.T.L. Lipid productivity as a key characteristic for choosing algal species for biodiesel production. *Journal of Applied Phycology* 2009, 21(5), 493–507.
 31. Merchant, S.S.; Kropat, J.; Liu, B.; Shaw, J.; Warakanont, J. TAG, you're it! *Chlamydomonas* as a reference organism for understanding algal triacylglycerol accumulation. *Current Opinion in Biotechnology* 2012, 23(3), 352–363.
 32. Knothe, G. Dependence of biodiesel fuel properties on the structure of fatty acid alkyl esters. *Fuel Processing Technology* 2005, 86(10), 1059–1070.



33. Chisti, Y. Biodiesel from microalgae beats bioethanol. *Trends in Biotechnology* 2008, 26(3), 126–131.
34. Jorquera, O.; Kiperstok, A.; Sales, E.A.; Embirucu, M.; Ghirardi, M.L. Comparative energy life-cycle analyses of microalgal biomass production in open ponds and photobioreactors. *Bioresource Technology* 2010, 101(4), 1406–1413.
35. Wijffels, R.H.; Barbosa, M.J. An outlook on microalgal biofuels. *Science* 2010, 329(5993), 796–799.
36. raggs, R.J.; Lundquist, T.J.; Benemann, J.R. Wastewater treatment and algal biofuel production. In *Algae for Biofuels and Energy*; Springer: Dordrecht, Netherlands, 2012; pp. 153–163.
37. Davis, R.; Aden, A.; Pienkos, P.T. Techno-economic analysis of autotrophic microalgae for fuel production. *Applied Energy* 2011, 88(10), 3524–3531.
38. Ugwu, C.U.; Aoyagi, H.; Uchiyama, H. Photobioreactors for mass cultivation of algae. *Bioresource Technology* 2008, 99(10), 4021–4028.
39. Benemann, J.R.; Oswald, W.J. *Systems and Economic Analysis of Microalgae Ponds for Conversion of CO₂ to Biomass*; DOE/PC/93204-T5; Department of Energy: Washington, DC, USA, 1996.
40. arvalho, A.P.; Meireles, L.A.; Malcata, F.X. Microalgal reactors: A review of enclosed system designs and performances. *Biotechnology Progress* 2006, 22(6), 1490–1506.
41. Molina, E.; Fernandez, J.; Acien, F.G.; Chisti, Y. Tubular photobioreactor design for algal cultures. *Journal of Biotechnology* 2001, 92(2), 113–131.
42. Degen, J.; Uebele, A.; Retze, A.; Schmid-Staiger, U.; Trosch, W. A novel airlift photobioreactor with baffles for improved light utilization through the flashing light effect. *Journal of Biotechnology* 2001, 92(2), 89–94.
43. Huntley, M.E.; Redalje, D.G. CO₂ mitigation and renewable oil from photosynthetic microbes: A new appraisal. *Mitigation and Adaptation Strategies for Global Change* 2007, 12(4), 573–608.
44. Rodolfi, L.; Zittelli, G.C.; Bassi, N.; Padovani, G.; Biondi, N.; Bonini, G.; Tredici, M.R. Microalgae for oil: Strain selection, induction of lipid synthesis and outdoor mass cultivation in a low-cost photobioreactor. *Biotechnology and Bioengineering* 2009, 102(1), 100–112.
45. Sukenik, A.; Levy, R.S.; Levy, Y.; Falkowski, P.G.; Dubinsky, Z. Optimizing algal biomass production in an outdoor pond: a simulation model. *Journal of Applied Phycology* 1991, 3(3), 191–201.
46. Goldman, J.C.; Carpenter, E.J. A kinetic approach to the effect of temperature on algal growth. *Limnology and Oceanography* 1974, 19(5), 756–766.
47. Mohsenpour, S.F.; Willoughby, N. Effect of CO₂ concentration on growth and lipid productivity of microalgae. *Bioresource Technology* 2013, 148, 585–589.
48. Grima, E.M.; Belarbi, E.H.; Acien Fernandez, F.G.; Robles Medina, A.; Chisti, Y. Recovery of microalgal biomass and metabolites: process options and economics. *Biotechnology Advances* 2003, 20(7–8), 491–515.
49. Barros, A.I.; Goncalves, A.L.; Simoes, M.; Pires, J.C.M. Harvesting techniques applied to microalgae: A review. *Renewable and Sustainable Energy Reviews* 2015, 41, 1489–1500.
50. Papazi, A.; Makridis, P.; Divanach, P. Harvesting *Chlorella minutissima* using cell



- coagulants. *Journal of Applied Phycology* 2010, 22(3), 349–355.
51. Vandamme, D.; Foubert, I.; Fraeye, I.; Meesschaert, B.; Muylaert, K. Flocculation of *Chlorella vulgaris* induced by high pH: Role of magnesium and calcium and practical implications. *Bioresource Technology* 2012, 105, 114–119.
 52. Salim, S.; Bosma, R.; Vermue, M.H.; Wijffels, R.H. Harvesting of microalgae by bio-flocculation. *Journal of Applied Phycology* 2011, 23(5), 849–855.
 53. Molina Grima, E.; Acien Fernandez, F.G.; Garcia Camacho, F.; Chisti, Y. Photobioreactors: light regime, mass transfer, and scaleup. *Journal of Biotechnology* 1999, 70(1–3), 231–247.
 54. Dassey, A.J.; Theegala, C.S. Harvesting economics and strategies using centrifugation for cost effective separation of microalgae cells for biodiesel applications. *Bioresource Technology* 2013, 128, 241–245.
 55. Bilad, M.R.; Vandamme, D.; Foubert, I.; Muylaert, K.; Vankelecom, I.F.J. Harvesting microalgal biomass using submerged microfiltration membranes. *Bioresource Technology* 2012, 111, 343–352.
 56. Danquah, M.K.; Gladman, B.; Moheimani, N.; Forde, G.M. Microalgal growth characteristics and subsequent influence on dewatering efficiency. *Chemical Engineering Journal* 2009, 151(1–3), 73–78.
 57. Gao, S.; Yang, J.; Tian, J.; Ma, F.; Tu, G.; Du, M. Electro-coagulation–flotation process for algae removal. *Journal of Hazardous Materials* 2010, 177(1–3), 336–343.
 58. Hanotu, J.; Bandulasena, H.C.H.; Zimmerman, W.B. Microflotation performance for algal separation. *Biotechnology and Bioengineering* 2012, 109(7), 1663–1673.
 59. Sathish, A.; Sims, R.C. Biodiesel from mixed culture algae via a wet lipid extraction procedure. *Bioresource Technology* 2012, 118, 643–647.
 60. Greenwell, H.C.; Laurens, L.M.L.; Shields, R.J.; Lovitt, R.W.; Flynn, K.J. Placing microalgae on the biofuels priority list: a review of the technological challenges. *Journal of the Royal Society Interface* 2010, 7(46), 703–726.
 61. Lee, A.K.; Lewis, D.M.; Ashman, P.J. Disruption of microalgal cells for the extraction of lipids for biofuels: processes and specific energy requirements. *Biomass and Bioenergy* 2012, 46, 89–101.
 62. Bligh, E.G.; Dyer, W.J. A rapid method of total lipid extraction and purification. *Canadian Journal of Biochemistry and Physiology* 1959, 37(8), 911–917.
 63. Ramos, M.J.; Fernandez, C.M.; Casas, A.; Rodriguez, L.; Perez, A. Influence of fatty acid composition of raw materials on biodiesel properties. *Bioresource Technology* 2009, 100(1), 261–268.
 64. Herrero, M.; Ibanez, E. Green processes and sustainability: An overview on the extraction of high added-value products from seaweeds and microalgae. *Journal of Supercritical Fluids* 2015, 96, 211–216.
 65. Andrich, G.; Nesti, U.; Venturi, F.; Zinnai, A.; Fiorentini, R. Supercritical fluid extraction of bioactive lipids from the microalga *Nannochloropsis* sp. *European Journal of Lipid Science and Technology* 2005, 107(6), 381–386.
 66. Crampon, C.; Mouahid, A.; Toudji, S.A.A.; Lepine, O.; Badens, E. Influence of pretreatment on supercritical CO₂ extraction from *Nannochloropsis oculata*. *Journal of Supercritical Fluids* 2013, 79, 337–344.
 67. Dong, T.; Knoshaug, E.P.; Davis, R.; Laurens, L.M.L.; Van Wychen, S.; Pienkos, P.T.;



- Nagle, N. Combined algal processing: A novel integrated biorefinery process to produce algal biofuels and bioproducts. *Algal Research* 2016, 19, 316–323.
68. Guo, Y.; Yeh, T.; Song, W.; Xu, D.; Wang, S. A review of bio-oil production from hydrothermal liquefaction of algae. *Renewable and Sustainable Energy Reviews* 2015, 48, 776–790.
69. Kim, D.G.; Hwang, K.R.; Choi, I.S.; Lee, J.S. Current status and future prospect of microalgae-derived energy and chemicals. *Journal of Industrial and Engineering Chemistry* 2015, 21, 11–22.
70. Ma, F.; Hanna, M.A. Biodiesel production: a review. *Bioresource Technology* 1999, 70(1), 1–15.
71. reedman, B.; Butterfield, R.O.; Pryde, E.H. Transesterification kinetics of soybean oil. *Journal of the American Oil Chemists' Society* 1986, 63(10), 1375–1380.
72. Vicente, G.; Martinez, M.; Aracil, J. Integrated biodiesel production: a comparison of different homogeneous catalysts systems. *Bioresource Technology* 2004, 92(3), 297–305.
73. ukuda, H.; Kondo, A.; Noda, H. Biodiesel fuel production by transesterification of oils. *Journal of Bioscience and Bioengineering* 2001, 92(5), 405–416.
74. Leung, D.Y.C.; Wu, X.; Leung, M.K.H. A review on biodiesel production using catalyzed transesterification. *Applied Energy* 2010, 87(4), 1083–1095.
75. Zabeti, M.; Wan Daud, W.M.A.; Aroua, M.K. Activity of solid catalysts for biodiesel production: A review. *Fuel Processing Technology* 2009, 90(6), 770–777.
76. Meher, L.C.; Vidya Sagar, D.; Naik, S.N. Technical aspects of biodiesel production by transesterification—a review. *Renewable and Sustainable Energy Reviews* 2006, 10(3), 248–268.
77. Macias-Sanchez, M.D.; Mantell, C.; Rodriguez, M.; Martinez de la Ossa, E.; Lubian, L.M.; Montero, O. Supercritical fluid extraction of carotenoids and chlorophyll a from *Synechococcus* sp. *Journal of Supercritical Fluids* 2009, 48(1), 23–26.
78. Rashid, U.; Anwar, F. Production of biodiesel through optimized alkaline-catalyzed transesterification of rapeseed oil. *Fuel* 2008, 87(3), 265–273.
79. nothe, G.; Steidley, K.R. Kinematic viscosity of biodiesel fuel components and related compounds. *Fuel* 2005, 84(9), 1059–1065.
80. Hoekman, S.K.; Broch, A.; Robbins, C.; Cenicerros, E.; Natarajan, M. Review of biodiesel composition, properties, and specifications. *Renewable and Sustainable Energy Reviews* 2012, 16(1), 143–169.
81. Stansell, G.R.; Gray, V.M.; Sym, S.D. Microalgal fatty acid composition: implications for biodiesel quality. *Journal of Applied Phycology* 2012, 24(4), 791–801.
82. Mofijur, M.; Masjuki, H.H.; Kalam, M.A.; Hazrat, M.A.; Liaquat, A.M.; Shahabuddin, M.; Varman, M. Prospects of biodiesel from *Jatropha* in Malaysia. *Renewable and Sustainable Energy Reviews* 2012, 16(7), 5007–5020.
83. Xue, J.; Grift, T.E.; Hansen, A.C. Effect of biodiesel on engine performances and emissions. *Renewable and Sustainable Energy Reviews* 2011, 15(2), 1098–1116.
84. Rakopoulos, C.D.; Antonopoulos, K.A.; Rakopoulos, D.C.; Hountalas, D.T.; Giakoumis, E.G. Comparative performance and emissions study of a direct injection diesel engine using blends of diesel fuel with vegetable oils or bio-diesels of various origins. *Energy Conversion and Management* 2006, 47(18–19), 3272–3287.

85. Lardon, L.; Helias, A.; Sialve, B.; Steyer, J.P.; Bernard, O. Life-cycle assessment of biodiesel production from microalgae. *Environmental Science & Technology* 2009, 43(17), 6475–6481.
86. Clarens, A.F.; Resurreccion, E.P.; White, M.A.; Colosi, L.M. Environmental life cycle comparison of algae to other bioenergy feedstocks. *Environmental Science & Technology* 2010, 44(5), 1813–1819.
87. Sills, D.L.; Paramita, V.; Franke, M.J.; Johnson, M.C.; Akabas, T.M.; Greene, C.H.; Tester, J.W. Quantitative uncertainty analysis of life cycle assessment for algal biofuel production. *Environmental Science & Technology* 2013, 47(2), 687–694.
88. [88] Brentner, L.B.; Eckelman, M.J.; Zimmerman, J.B. Combinatorial life cycle assessment to inform process design of industrial production of algal biodiesel. *Environmental Science & Technology* 2011, 45(16), 7060–7067.
89. Douskova, I.; Doucha, J.; Livansky, K.; Machat, J.; Novak, P.; Umysova, D.; Zachleder, V.; Vitova, M. Simultaneous flue gas bioremediation and reduction of microalgal biomass production costs. *Applied Microbiology and Biotechnology* 2009, 82(1), 179–185.
90. Pires, J.C.M.; Alvim-Ferraz, M.C.M.; Martins, F.G.; Simoes, M. Carbon dioxide capture from flue gases using microalgae: Engineering aspects and biorefinery concept. *Renewable and Sustainable Energy Reviews* 2012, 16(5), 3043–3053.
91. Sun, A.; Davis, R.; Starbuck, M.; Ben-Amotz, A.; Pate, R.; Pienkos, P.T. Comparative cost analysis of algal oil production for biofuels. *Energy* 2011, 36(8), 5169–5179.
92. Richardson, J.W.; Johnson, M.D.; Outlaw, J.L. Economic comparison of open pond raceways to photo bio-reactors for profitable production of algae for transportation fuels in the Southwest. *Algal Research* 2012, 1(1), 93–100.
93. Norsker, N.H.; Barbosa, M.J.; Vermue, M.H.; Wijffels, R.H. Microalgal production—A close look at the economics. *Biotechnology Advances* 2011, 29(1), 24–27.
94. Acien, F.G.; Fernandez, J.M.; Magan, J.J.; Molina, E. Production cost of a real microalgae production plant and strategies to reduce it. *Biotechnology Advances* 2012, 30(6), 1344–1353.
95. Benemann, J. Microalgae for biofuels and animal feeds. *Energies* 2013, 6(11), 5869–5886.
96. Batan, L.; Quinn, J.; Wahlen, B.; Bradley, T. Net energy and greenhouse gas emission evaluation of biodiesel derived from microalgae. *Environmental Science & Technology* 2010, 44(20), 7975–7980.
97. Xu, L.; Weathers, P.J.; Xiong, X.R.; Liu, C.Z. Microalgal bioreactors: Challenges and opportunities. *Engineering in Life Sciences* 2009, 9(3), 178–189.
98. Hannon, M.; Gimpel, J.; Tran, M.; Rasala, B.; Mayfield, S. Biofuels from algae: challenges and potential. *Biofuels* 2010, 1(5), 763–784.
99. Stephens, E.; Ross, I.L.; King, Z.; Mussnug, J.H.; Kruse, O.; Posten, C.; Borowitzka, M.A.; Hankamer, B. An economic and technical evaluation of microalgal biofuels. *Nature Biotechnology* 2010, 28(2), 126–128.
100. Hlavova, M.; Turoczy, Z.; Bisova, K. Improving microalgae for biotechnology—From genetics to synthetic biology. *Biotechnology Advances* 2015, 33(6), 1194–1203.
101. Radakovits, R.; Jinkerson, R.E.; Darzins, A.; Posewitz, M.C. Genetic engineering of algae for enhanced biofuel production. *Eukaryotic Cell* 2010, 9(4), 486–501.



102. Msanne, J.; Xu, D.; Konda, A.R.; Casas-Mollano, J.A.; Awada, T.; Cahoon, E.B.; Cerutti, H. Metabolic and gene expression changes triggered by nitrogen deprivation in the photoautotrophically grown microalgae *Chlamydomonas reinhardtii* and *Coccomyxa* sp. C-169. *Phytochemistry* 2012, 75, 50–59.
103. Gonzalez-Fernandez, C.; Ballesteros, M. Linking microalgae and cyanobacteria culture conditions and key-enzymes for carbohydrate accumulation. *Biotechnology Advances* 2012, 30(6), 1655–1661.
104. Santos-Ballardo, D.U.; Rossi, S.; Hernandez, V.; Gomez Valdez, R.; Balois, R.; Avila-Alejandre, A.X.; Fernandez-Herrera, E.; de la Cruz-Lazaro, E.; Bastidas-Bastidas, P.J. A simple spectrophotometric method for biomass measurement of important microalgae species in aquaculture. *Aquaculture* 2015, 448, 87–92.
105. Nautiyal, P.; Subramanian, K.A.; Dastidar, M.G. Production and characterization of biodiesel from algae. *Fuel Processing Technology* 2014, 120, 79–88.
106. Tran, D.T.; Chen, C.L.; Chang, J.S. Immobilization of *Burkholderia* sp. lipase on a ferric silica nanocomposite for biodiesel production. *Journal of Biotechnology* 2012, 158(3), 112–119.
107. Wang, X.; Cai, Z.; Liu, X.; Zhang, J.; Tian, R. Effects of gold nanoparticles on the growth and photosynthetic efficiency of *Chlorella vulgaris*. *Ecotoxicology* 2013, 22(8), 1234–1241.
108. Ruiz, J.; Olivieri, G.; De Vree, J.; Bosma, R.; Willems, P.; Reith, J.H.; Eppink, M.H.M.; Kleinegris, D.M.M.; Wijffels, R.H.; Barbosa, M.J. Towards industrial products from microalgae. *Energy & Environmental Science* 2016, 9(10), 3036–3043.
109. Harun, R.; Singh, M.; Forde, G.M.; Danquah, M.K. Bioprocess engineering of microalgae to produce a variety of consumer products. *Renewable and Sustainable Energy Reviews* 2010, 14(3), 1037–1047.
110. Craggs, R.; Sutherland, D.; Campbell, H. Hectare-scale demonstration of high rate algal ponds for enhanced wastewater treatment and biofuel production. *Journal of Applied Phycology* 2012, 24(3), 329–337.

HOW TO CITE: Shravani Jadhao, Shivprasad Dhage, Microalgae-Based Biodiesel as a Sustainable Renewable Energy Source: A Comprehensive Review, *Int. J. of Pharm. Sci.*, 2026, Vol 4, Issue 6, 4194-4213, <https://doi.org/10.5281/zenodo.20730674>

