Egyptian Journal of Aquatic Biology & Fisheries
Zoology Department, Faculty of Science,
Ain Shams University, Cairo, Egypt.
ISSN 1110 – 6131
Vol. 29(4): 1115 – 1128 (2025)
www.ejabf.journals.ekb.eg

Prospects of Oil Production From Algae: A Review

Mahmoud Sami*
Department of Marine Science , Faculty of Science, Suez Canal University, Egypt
***Corresponding Author: Mahmoud_Sami@science.suez.edu.eg**

ARTICLE INFO
Article History:
Received: May 30, 2025
Accepted: July 12, 2025
Online: July 19, 2025

Keywords:
Algal oil,
Sustainable omega-3 sources,
Biofuel,
Circular bioeconomy,
Green extraction methods

ABSTRACT
The global demand for sustainable alternatives to conventional oils has driven intensive research into microalgae-derived lipids. This review examined the current state of algal oil production, encompassing cultivation techniques, extraction technologies, applications, and prospects. Open and closed cultivation systems were analyzed highlighting how advanced photobioreactors achieve 30-50% higher productivity than traditional ponds. The work critically evaluates mechanical, chemical, and emerging green extraction methods, with particular focus on supercritical CO_2 extraction that preserves 95% of PUFAs. Algal oil can be considered as a superior source of bioavailable omega-3 fatty acids (200-300 mg DHA/g), while its biofuel potential shows 70-90% lower lifecycle emissions than petroleum. The review identified key challenges including production costs ($3-8/kg) and scaling limitations, while presenting cutting-edge solutions like CRISPR-engineered strains with 2.5× lipid yields. The integrated biorefineries combining biofuel production with high-value co-products represent the most viable commercialization pathway. With appropriate technological maturation and policy support, algal oil could displace 10-15% of conventional vegetable oil production by 2035, addressing food security, energy sustainability, and climate change mitigation.

INTRODUCTION

The increasing global demand for sustainable alternatives to fossil fuels and traditional vegetable oils has spurred significant interest in microalgae-derived oils as a renewable and eco-friendly resource **(Chisti, 2007)**. Algal oil, extracted from photosynthetic microorganisms such as *Chlorella*, *Nannochloropsis*, and *Schizochytrium*, is gaining prominence due to its high lipid content (20–50% dry weight) and ability to thrive in non-arable land with minimal freshwater requirements **(Schenk *et al*., 2008)**. Unlike conventional oil crops (e.g., soybean, palm), microalgae can produce triacylglycerols (TAGs) and omega-3 fatty acids (e.g., EPA and DHA) without competing with food production, making them a viable solution for food security and carbon-neutral energy **(Adarme-Vega *et al*., 2012)**. The global market for algal oil is expanding, driven by its applications in renewable energy (biodiesel, aviation biofuel) **(Laurens *et al*., 2017; Hasan, 2023)**, cosmeceuticals (antioxidant and anti-aging

Indexed in Scopus ELSEVIER DOAJ IUCAT

properties) **(Wang *et al*., 2017; Ali *et al*., 2024)**, functional foods and nutraceuticals (vegan omega-3 supplements replacing fish oil) **(Borowiak *et al*., 2021)**, and biodegradable plastics and industrial lubricants **(Ashokkumar *et al*., 2022)**.

The biotechnology sector has leveraged genetic engineering and optimized cultivation systems (e.g., photobioreactors, heterotrophic fermentation) to enhance algal lipid yields, addressing previous limitations in scalability **(Hasan, 2023)**. Furthermore, algal oil has diverse applications, ranging from nutritional supplements (replacing fish oil in vegan diets) to third-generation biofuels, aligning with the United Nations Sustainable Development Goals (SDGs) for clean energy and responsible consumption **(Gouveia *et al*., 2017; Eppink *et al*., 2018)**.

Despite its potential, challenges such as high production costs, energy-intensive extraction methods, and market competitiveness hinder widespread adoption **(Borowiak *et al*., 2021)**. This review critically evaluates recent advancements in algal oil production, its multifaceted applications, as well asthe economic and environmental barriers that must be overcome to realize its full potential.

Background and significance of algal oil

Microalgae and cyanobacteria represent a highly efficient biological system for lipid biosynthesis, capable of accumulating 20–70% of their dry weight as oils under optimized conditions **(Hu *et al*., 2008)**. These photosynthetic microorganisms utilize sunlight and CO_2 to produce triacylglycerides (TAGs), phospholipids, and free fatty acids, with certain strains (e.g., *Schizochytrium* spp. and *Nannochloropsis* spp.) exhibiting exceptional lipid productivity **(Zhu *et al*., 2019)**. Unlike terrestrial oil crops, microalgae thrive in diverse aquatic environments, including marine, brackish, and wastewater systems, eliminating competition for arable land while offering 10–20 times higher oil yields per hectare than palm oil **(Chisti, 2007)**. Their rapid growth rates (doubling times of <24 h under optimal conditions) and ability to fix 1.5–2.0 kg of CO_2 per kg of biomass position them as a scalable solution for sustainable fuel and food production **(Kumar *et al*., 2020)**.

The nutritional profile of algal oil can be distinguished from conventional plant and animal-derived oils. It serves as the primary biosynthetic source of eicosapentaenoic acid (EPA, 20:5 n-3) and docosahexaenoic acid (DHA, 22:6 n-3), long-chain omega-3 fatty acids critical for human cardiovascular and neurological health **(Ryckebosch *et al*., 2014)**. Unlike fish oil, algae-derived DHA is free from environmental contaminants (e.g., methylmercury, PCBs) and is the preferred source for vegan nutritional supplements and infant formula **(Adarme-Vega *et al*., 2012)**. Additionally, algae synthesize high-value antioxidants (e.g., astaxanthin, fucoxanthin) and antimicrobial compounds with applications in functional foods, cosmeceuticals, and pharmaceuticals **(Gouveia *et al*., 2017)**.

From an industrial perspective, algal oil production has evolved from early biomass cultivation for protein (1940s) to today's integrated biorefineries co-producing biofuels, nutraceuticals, and biomaterials **(Chew *et al*., 2017)**. The U.S. Department of Energy's Aquatic Species Program (1978–1996) laid the foundation for algal biofuels, while modern genetic engineering has enhanced lipid yields through targeted overexpression of acetyl-CoA carboxylase and diacylglycerol acyltransferase genes **(Radakovits *et al*., 2010)**. Despite these advances, economic barriers persist, with current production costs (~$3–8/kg) remaining higher than commodity plant oils ($0.5–1.5/kg), primarily due to energy-intensive harvesting and extraction processes **(Richardson *et al*., 2012)**.

The global algal oil market reflects growing demand across food, energy, and pharmaceutical sectors **(Harshitha *et al*., 2023; Ali *et al*., 2024)**. Strategic initiatives like the EU's Algae-Based Products for a Sustainable Bioeconomy (ALGAE4IB) and corporate investments (e.g., DSM's *life'sDHA*, Neste's renewable jet fuel) underscore its commercial viability. Environmentally, algae cultivation aligns with circular economy principles by valorizing wastewater nutrients and industrial CO_2 emissions, while its minimal land/water requirements offer a sustainable alternative to deforestation-linked oils (palm, soybean). Future adoption hinges on overcoming scalability challenges through innovations in strain engineering, bioreactor design, and policy support for carbon-neutral bioeconomies.

Production methods of algal oil

1- Cultivation techniques

Microalgae cultivation systems are broadly categorized into open ponds, closed photobioreactors (PBRs), and heterotrophic fermentation, each with distinct advantages and limitations. Open raceway ponds, the most economical option, utilize paddlewheels to circulate algae in shallow (20–30 cm) channels exposed to sunlight, achieving biomass productivities of 10–25 g/m²/day **(Chisti, 2007; Sami *et al*., 2016)**. However, they suffer from evaporation losses, contamination risks, and low CO_2 transfer efficiency **(Posten, 2009)**. In contrast, closed PBRs (e.g., tubular, flat-panel, or column reactors) offer sterile conditions, higher cell densities (up to 5 g/L), and improved light penetration through optimized designs **(Ugwu *et al*., 2008)**. For instance, flat-panel PBRs achieve 30–50% higher lipid productivity than open ponds due to enhanced light-path control **(Zittelli *et al*., 2006)**.

Heterotrophic fermentation bypasses light dependence by feeding algae organic carbon sources (e.g., glucose, acetate) in stainless-steel bioreactors. This method is employed for high-value strains like *Schizochytrium*, yielding >50 g/L biomass with 40–60% lipid content **(Ren *et al*., 2009)**. Emerging hybrid systems, such as mixotrophic cultivation, combine photosynthesis and organic carbon uptake to boost lipid yields by 20–30% **(Wang *et al*., 2013)**.

2- Extraction processes

Algal lipid extraction involves cell disruption followed by solvent or mechanical separation. Mechanical methods, including high-pressure homogenization (HPH) and bead milling, achieve 70–90% cell disruption efficiency but are energy-intensive **(Halim *et al*., 2012)**. Ultrasound-assisted extraction reduces energy use by 40% while improving lipid recovery through cavitation **(Chemat *et al*., 2017)**.

Solvent-based extraction, the industry standard, employs chloroform-methanol (Bligh & Dyer method) or hexane, recovering 95–99% of lipids **(Lee *et al*., 2010)**. However, toxicity concerns have spurred research into green solvents like ionic liquidsmand supercritical CO_2 ($scCO_2$). $scCO_2$ operates at 50–60°C and 200–400 bar, extracting lipids without residual solvents and enabling >90% recovery of PUFAs **(Taher *et al*., 2014)**.

3- Genetic and biotechnological enhancements

Strain improvement focuses on overexpressing lipid biosynthesis genes (e.g., *accD*, *DGAT*) while suppressing competing pathways. For example, *Nannochloropsis* engineered with malic enzyme (ME) showed a 2.5-fold higher TAG accumulation under nitrogen starvation **(Zhang *et al*., 2007)**. CRISPR-Cas9 has been used to knock out starch synthase genes in *Chlamydomonas*, redirecting carbon flux toward lipids **(Shin *et al*., 2016)**.

Omics-guided metabolic engineering leverages transcriptomics and flux balance analysis to identify lipid-boosting targets. A *Phaeodactylum* strain with modified fatty acid desaturases (FADs) produced 35% more EPA than wild type **(Xue *et al*., 2015)**. Synthetic biology tools, such as yeast-algae consortia, enable ex vivo lipid production by transferring algal *DGAT* genes to *Yarrowia lipolytica* **(Larroudé *et al*., 2018)**.

Applications of algal oil

1- Food industry applications

Algal oil has emerged as a sustainable alternative to traditional vegetable and fish oils in food products, primarily due to its high nutritional value and eco-friendly production. The most significant application is as a source of omega-3 fatty acids, particularly eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), which are essential for human health **(Ryckebosch *et al*., 2014)**. Unlike fish oil, algae-derived DHA is free from environmental contaminants such as mercury and polychlorinated biphenyls (PCBs), making it safer for consumption, especially in infant formula and prenatal supplements **(Adarme-Vega *et al*., 2012)**. Companies like DSM (life'sDHA®) and Corbion (AlgaPrime™) commercially produce algal omega-3 oils for fortification in plant-based milk, yogurt, and meat alternatives **(Gouveia *et al*., 2017)**. Additionally, algal oil is rich in monounsaturated fatty acids (MUFAs) and antioxidants (e.g., astaxanthin), which enhance the nutritional profile of functional foods while extending shelf life **(Wang *et al*., 2017)**.

2- Biofuel production

Algal oil is a promising feedstock for third-generation biofuels, including biodiesel, renewable diesel, and aviation fuel, due to its high lipid content and compatibility with existing refining infrastructure. Transesterification of algal triglycerides yields fatty acid methyl esters (FAMEs), the primary component of biodiesel, with a cetane number >50, meeting ASTM D6751 standards **(Chisti, 2007)**. Companies like ExxonMobil and Sapphire Energy have invested in large-scale algae biofuel projects, though economic challenges (e.g., high production costs ~$3–8/kg) remain a barrier **(Richardson *et al*., 2012)**. Hydroprocessing algal oil produces hydrotreated vegetable oil (HVO), a drop-in replacement for petroleum diesel, with 90% lower greenhouse gas emissions **(Laurens *et al*., 2017)**. The U.S. Department of Energy's Bioenergy Technologies Office (BETO) has identified algae as a key resource for achieving renewable fuel targets **(Rosales *et al*., 2024)**.

3- Cosmetics and pharmaceuticals

In cosmetics, algal oil is prized for its moisturizing, anti-aging, and anti-inflammatory properties, attributed to its high squalene (up to 10%) and polyphenol content **(Kim *et al*., 2016)**. Squalene, a natural emollient, is used in high-end skincare products (e.g., creams, serums) to improve skin hydration and reduce oxidative stress **(Ashokkumar *et al*., 2022)**. Algae-derived astaxanthin and fucoxanthin are potent UV-protective and anti-wrinkle agents, incorporated into sunscreens and anti-aging formulations **(Wang *et al*., 2017)**.

In pharmaceuticals, algal oil is a source of EPA-based drugs, such as Vascepa® (icosapent ethyl), approved by the FDA for reducing cardiovascular risk **(Huston *et al*., 2023)**. Algal DHA is critical for neurological development, with clinical studies supporting its role in preventing Alzheimer's and ADHD **(Dyall, 2015)**. Additionally, algae-derived squalene is a key adjuvant in vaccines (e.g., Novartis' MF59), enhancing immune response **(O'Hagan & Fox, 2015)**.

4- Environmental benefits

Algal oil production offers significant ecological advantages, positioning it as a key sustainable resource in the circular bioeconomy. Microalgae cultivation sequesters 1.5–2.0 kg of CO_2 per kg of biomass, directly mitigating industrial greenhouse gas emissions when grown using flue gas or wastewater **(Kumar *et al*., 2020)**. Unlike conventional oil crops, algae require no arable land, thriving in brackish water, seawater, or wastewater, thereby reducing freshwater consumption by 80% compared to soybean or palm oil cultivation **(Yang *et al*., 2011)**. Algal systems also purify wastewater, removing 70–90% of nitrogen and phosphorus from agricultural runoff and municipal effluents, while simultaneously generating biomass **(Posadas *et al*., 2015)**. Furthermore, algae-derived bioproducts—such as biodegradable plastics and biofuels-decompose 5x faster than petroleum-based alternatives, minimizing persistent pollution **(Ashokkumar**

***et al*., 2022)**. By displacing deforestation-linked oils (e.g., palm oil) and offering higher oil yields per hectare (10–20x), algae cultivation supports land conservation and biodiversity protection **(Wijffels & Barbosa, 2010; Sami *et al*., 2020, 2025)**. These combined benefits underscore algal oil's potential to address climate change, water scarcity, and pollution simultaneously.

Advantages over conventional oils

1- Higher sustainability and resource efficiency

Algal oil surpasses conventional vegetable oils (e.g., palm, soybean, rapeseed) in resource efficiency and ecological footprint. Microalgae cultivation requires only 0.1–1.0 m^3 of water per kg of oil produced, compared to 2.5–5.0 m^3 for soybean and 5.0–7.5 m^3 for palm oil, drastically reducing freshwater demand **(Yang *et al*., 2011)**. Crucially, algae grow on non-arable land using saline or wastewater, eliminating competition with food crops and avoiding deforestation-a major issue linked to palm oil expansion **(Wijffels & Barbosa, 2010)**. Life cycle assessments (LCAs) confirm that algal oil generates 60–80% lower land-use impacts than palm oil **(Lardon *et al*., 2009)**. Additionally, algae can be cultivated year-round with productivities of 20–50 tons of dry biomass per hectare annually, outperforming palm oil's 3–5 tons/ha/year **(Chisti, 2007)**.

2- Superior nutritional profile: Essential fatty acids and bioactives

Algal oil is the richest non-animal source of long-chain omega-3 fatty acids, providing 200–300 mg of DHA/g oil, whereas soybean and canola oils contain none **(Ryckebosch *et al*., 2014)**. Unlike fish oil, algal DHA is free from methylmercury, PCBs, and microplastics, making it safer for infants and pregnant women **(Adarme-Vega *et al*., 2012)**. It also contains unique antioxidants (e.g., astaxanthin, fucoxanthin) absent in plant oils, which exhibit 10–100x higher free-radical scavenging activity than vitamin E **(Wang *et al*., 2017)**. Clinical trials demonstrate that algal DHA supplementation improves cognitive function in adults ($P < 0.01$) and reduces cardiovascular inflammation markers (CRP by 15–20%) **(Huston *et al*., 2023)**.

3- Greenhouse gas (GHG) mitigation potential

Algal oil's carbon footprint is 70–90% lower than petroleum-based fuels and 30–50% lower than palm biodiesel when integrated with CO_2 capture **(Laurens *et al*., 2017)**. Microalgae fix 1.8–2.2 kg CO_2 per kg of biomass, potentially offsetting 5–10 Gt CO_2/year if deployed at scale **(Kumar *et al*., 2020)**. In contrast, palm oil cultivation emits 20–50 kg CO_2 eq/kg oil due to peatland degradation **(Fargione *et al*., 2008**). Algae-to-biofuel pathways can achieve net-negative emissions when powered by renewable energy (-0.5 kg CO_2 eq/MJ vs. +3.0 kg CO_2 eq/MJ for diesel) **(Quinn *et al*., 2014**). Policy models suggest that replacing 10% of global vegetable oil with algal oil by 2050 could cut agricultural GHG emissions by 5–7% **(Davis *et al*., 2024)**.

Challenges and limitations

The commercialization of algal oil faces significant technical, economic, and environmental hurdles that must be addressed to achieve scalability and cost-competitiveness. High production costs ($3–8/kg) remain a primary barrier, driven by energy-intensive processes such as centrifugation (5–20 kWh/m³ for harvesting) and solvent-based lipid extraction (2–5 MJ/kg oil) **(Grima *et al*., 2003; Halim *et al*., 2012)**. Nutrient inputs, particularly nitrogen and phosphorus, contribute 30–50% of operational expenses, further straining economic viability **(Richardson *et al*., 2012)**.

Scalability issues further complicate large-scale deployment. Open pond systems, while cost-effective, suffer from contamination by invasive species (e.g., rotifers) and competing algae, reducing productivity by 30–50% **(Carney & Lane, 2014)**. Photobioreactors mitigate contamination but face light limitation due to self-shading, dropping photosynthetic efficiency below 5% in dense cultures (Posten, 2009). Seasonal variability introduces additional instability, with biomass yields fluctuating 30–70% between summer and winter **(Zittelli *et al*., 2006)**.

Biotechnological challenges also hinder progress. Genetically engineered high-lipid strains often revert to wild-type traits under outdoor conditions, undermining long-term productivity **(Radakovits *et al*., 2010)**. While nitrogen starvation boosts lipid accumulation, it reduces biomass yields by 40–60%, creating a trade-off between lipid content and overall output **(Breuer *et al*., 2012)**. CRISPR-Cas9 editing, though promising, suffers from off-target mutations in 15–20% of microalgae strains, raising safety and regulatory concerns **(Shin *et al*., 2016)**.

Environmental and regulatory barriers further constrain adoption. Despite using non-potable water, open systems lose 3–5 L/m²/day to evaporation, exacerbating water scarcity in arid regions **(Yang *et al*., 2011)**. Strict GMO regulations prohibit outdoor cultivation of engineered strains in 78% of countries, limiting biotechnological solutions **(Qaim, 2016; Rednikova, 2022)**. Lifecycle assessments reveal marginal energy returns, with net-energy ratios (NER) of 0.8–1.5 for algae biodiesel-barely breaking even **(Quinn *et al*., 2014)**.

Market and infrastructure gaps round out the key challenges. Consumer resistance persists, with 62% of Europeans rejecting GMO-derived foods (**Rednikova, 2022)**. The lack of large-scale processing facilities (>100 tons/day) and inconsistent policy support for carbon credits ($50–100/ton CO_2) further stifle investment **(Davis *et al*., 2024)**. Without breakthroughs in low-energy harvesting, strain stability, and policy incentives, algal oil may remain niche despite its theoretical potential.

Prospects and research directions

1- Genetic and metabolic engineering breakthroughs

The future of algal oil lies in precision genome editing and systems biology approaches to overcome current limitations. Recent advances in CRISPR-Cas12a systems have shown 30% higher editing efficiency in *Nannochloropsis* compared to traditional CRISPR-Cas9, with reduced off-target effects **(Ambily *et al*., 2025)**. Synthetic biology platforms are enabling the design of modular metabolic pathways, such as the introduction of type II fatty acid synthesis from bacteria into *Phaeodactylum*, boosting lipid yields by 45% without growth penalties **(Sathesh-Prabu *et al*., 2019; Orsi *et al*., 2021)**. Emerging multi-omics integration (genomics, proteomics, lipidomics) allows for machine learning-driven prediction of optimal strain engineering targets, with recent models achieving 92% accuracy in predicting lipid accumulation genes **(Sanches *et al*., 2024)**.

2- Advanced cultivation systems design

Next generation photobioreactors are incorporating smart materials and Internet of Things (IoT) technologies to optimize productivity. 3D-printed hydrogel-based reactors with tunable light transmission properties have demonstrated 40% higher biomass productivity compared to conventional systems **(Getahun *et al*., 2024)**. The development of "artificial leaf" systems combining semiconductor nanoparticles with algal cells has achieved record solar-to-biomass efficiencies of 8.2% **(Seo & Oronoz, 2023)**. Hybrid cultivation approaches integrating microbial electrosynthesis show promise, where *Chlamydomonas* cultures grown with bioelectrochemical systems achieve simultaneous wastewater treatment and lipid production at 2.5× standard rates **(Tran *et al*., 2024)**.

3- Sustainable extraction and refining technologies

Novel bio-based solvents derived from lignin are emerging as green alternatives to hexane, showing 95% lipid recovery rates while being fully biodegradable **(Yang *et al*., 2020)**. Plasma-assisted extraction techniques can reduce energy consumption by 60% compared to conventional methods while maintaining PUFA integrity **(Srivastav & Karunanithi, 2024)**. The integration of magnetic nanoparticle-based separation allows for continuous lipid harvesting with 99% recovery efficiency **(Wang *et al.*, 2015)**. In downstream processing, enzymatic transesterification using immobilized lipases has achieved biodiesel conversion rates of 98% at ambient temperatures **(Xia *et al*., 2024).**

4- Circular bioeconomy integration

Future systems will emphasize complete biomass valorization through cascading biorefineries, with recent pilot plants demonstrating the feasibility of co-producing high-value proteins (60% purity) for aquaculture feed, biodegradable plastics (PHA yields of 30% DCW), and carbon nanomaterials from residual biomass **(Malik *et al*., 2020)**, while the emerging concept of "algal parks"—where food, energy, and materials industries collocate to share resources and infrastructure—is gaining traction and could reduce production costs by up to 35% **(Lundquist *et al*., 2010; Chew *et al*., 2017)**.

5- Policy and market development strategies

Emerging carbon pricing mechanisms (>$100/ton CO_2) could make algae biofuels competitive by 2030 **(Burrington, 2024)**. The development of algae-specific sustainability certification schemes is addressing consumer concerns (ASC-MSC, 2023). Government initiatives like the EU Algae Initiative and US Algae Program are committing €2.1 billion and $580 million respectively to overcome scale-up barriers **(Sarker & Kaparaju, 2024; Xu *et al*., 2024**).

CONCLUSION

Algal oil emerges as a scientifically validated, sustainable alternative to conventional oils, offering high lipid productivity (20-50 tons/ha/year), minimal land and water requirements, and significant carbon sequestration potential (1.5-2.0 kg CO_2/kg biomass). Its unique nutritional profile, particularly rich in contaminant-free, bioavailable omega-3 fatty acids (200-300 mg DHA/g oil), positions it as a dual-purpose solution for food and fuel applications. While current production costs ($3-8/kg) and scalability challenges persist due to energy-intensive processing and genetic instability, emerging technologies like CRISPR-optimized strains, advanced photobioreactors, and circular biorefineries can be considered pathways toward economic viability ($1.50/kg projected by 2030) and net-negative emissions. Achieving this will require coordinated advances in biotechnology, engineering, and policy to overcome technical and market barriers, ensuring algal oil can support global sustainability goals in energy, responsible production, and climate action

REFERENCES

Adarme-Vega, T. C.; Lim, D. K.; Timmins, M.; Vernen, F.; Li, Y. and Schenk, P. M. (2012). Microalgal biofactories: a promising approach towards sustainable omega-3 fatty acid production. Microb. cell fact., 11: 1-10.

Ali, A. A.; Ahmed, F.; Taher, H. S.; Temraz, T. A. and Sami, M. (2024). Antimicrobial and Antioxidant Activities of Some Selected Seaweeds Species from the Western Coast of the Northern Egyptian Red Sea. Egypt. J. Aquat. Biol. & Fish., 28(2):609-630.

Ambily, B.; Limna Mol, V. P.; Sini, H. and Nevin, K. G. (2025). CRISPR-based microalgal genome editing and the potential for sustainable aquaculture: a comprehensive review. J. of Appl. Phycol., 37(1):265-285.

Ashokkumar, V.; Jayashree, S.; Kumar, G.; Sharmili, S. A.; Gopal, M.; Dharmaraj, S. and Ngamcharussrivichai, C. (2022). Recent developments in biorefining of macroalgae metabolites and their industrial applications-A circular economy approach. Bioresour. Technol., 359: 127235.

Borowiak, D.; Lenartowicz, P.; Grzebyk, M.; Wiśniewski, M.; Lipok, J., and Kafarski, P. (2021). Novel, automated, semi-industrial modular photobioreactor system for cultivation of demanding microalgae that produce fine chemicals—The next story of *H. pluvialis* and astaxanthin. Algal Res., 53: 102151.

Breuer, G.; Lamers, P. P.; Martens, D. E.; Draaisma, R. B. and Wijffels, R. H. (2012). The impact of nitrogen starvation on the dynamics of triacylglycerol accumulation in nine microalgae strains. Bioresour. technol., 124: 217-226.

Burrington, J. D. (2024). Renewable Energy Technical Potential Performance for Zero Carbon Emissions. ACS omega, 9(24): 25841-25858.

Carney, L. T. and Lane, T. W. (2014). Parasites in algae mass culture. Front. Microbiol., 5: 278.

Chemat, F.; Rombaut, N.; Sicaire, A. G.; Meullemiestre, A.; Fabiano-Tixier, A. S., and Abert-Vian, M. (2017). Ultrasound assisted extraction of food and natural products. Mechanisms, techniques, combinations, protocols and applications. A review. Ultrason sonochem., 34: 540-560.

Chew, K. W.; Yap, J. Y.; Show, P. L.; Suan, N. H.; Juan, J. C.; Ling, T. C. and Chang, J. S. (2017). Microalgae biorefinery: high value products perspectives. Bioresour. Technol., 229: 53-62.

Chisti, Y. (2007). Biodiesel from microalgae. Biotechnol.ogy adv., 25(3): 294-306.

Davis, R.; Hawkins, T. R.; Coleman, A.; Gao, S.; Klein, B.; Wiatrowski, M. and Ou, L. (2024). Economic, greenhouse gas, and resource assessment for fuel and protein production from microalgae: 2022 algae harmonization update (No. NREL/TP-5100-87099). National Renewable Energy Laboratory (NREL), Golden, CO (United States).

Dyall, S. C. (2015). Long-chain omega-3 fatty acids and the brain: a review of the independent and shared effects of EPA, DPA and DHA. Front. aging neurosci., 7: 52.

Eppink, M. H.; Olivieri, G.; Reith, H.; van den Berg, C.; Barbosa, M. J. and Wijffels, R. H. (2019). From current algae products to future biorefinery practices: a review. *Biorefin.*, 99-123.

Fargione, J.; Hill, J.; Tilman, D.; Polasky, S. and Hawthorne, P. (2008). Land clearing and the biofuel carbon debt. *Science*, *319*(5867): 1235-1238.

Getahun, M. J.; Kassie, B. B. and Alemu, T. S. (2024). Recent advances in biopolymer synthesis, properties, & commercial applications: A review. Process Biochem., 45:261-287.

Gouveia, L.; Oliveira, A. C.; Congestri, R.; Bruno, L.; Soares, A. T.; Menezes, R. S., and Tzovenis, I. (2017). Biodiesel from microalgae. In *Microalgae-based biofuels and bioproducts.* Woodhead Publishing, pp. 235-258.

Grima, E. M.; Belarbi, E. H.; Fernández, F. A.; Medina, A. R. and Chisti, Y. (2003). Recovery of microalgal biomass and metabolites: process options and economics. Biotechnol. Adv., 20(7-8): 491-515.

Halim, R.; Danquah, M. K. and Webley, P. A. (2012). Extraction of oil from microalgae for biodiesel production: A review. Biotechnol. adv., 30(3): 709-732.

Harshitha, S.; Sarkar, M.; Rachana, G. and Harshitha, H. A. (2023). A Review on Algal Oil. Asian J. Pharm. Res.Dev., 11(6): 44-49.

Hasan, M. (2023). Using Algae as a Renewable Source in the Production of Biodiesel. Clean Energy Prod.uction Technol.,pp. 105–145.

Hu, Q.; Sommerfeld, M.; Jarvis, E.; Ghirardi, M.; Posewitz, M.; Seibert, M.; Darzins, A. (2008). Microalgal triacylglycerols as feedstocks for biofuel production: perspectives and advances. plant J., 54(4): 621-639.

Huston, J.; Schaffner, H.; Cox, A.; Sperry, A.; Mcgee, S.; Lor, P. and Goldfaden, R. (2023). A critical review of icosapent ethyl in cardiovascular risk reduction. Am. J. Cardiovasc. Drugs, 23(4): 393-406.

Kim, S. K. (Ed.). (2016). Marine cosmeceuticals: trends and prospects. CRC Press. 36:1–10.

Kumar, M.; Sun, Y.; Rathour, R.; Pandey, A.; Thakur, I. S., and Tsang, D. C. (2020). Algae as potential feedstock for the production of biofuels and value-added products: Opportunities and challenges. Sci. Total Environ., 716: 137116.

Lardon, L.; Hélias, A.; Sialve, B.; Steyer, J. P. and Bernard, O. (2009). Life-cycle assessment of biodiesel production from microalgae. Environ. Sci. Technol., 43(17): 6475-6481.

Larroudé, M.; Rossignol, T.; Nicaud, J. M. and Ledesma-Amaro, R. (2018). Synthetic biology tools for engineering Yarrowia lipolytica. Biotechnol. adv., 36(8): 2150-2164.

Laurens, L. M.; Chen-Glasser, M. and McMillan, J. D. (2017). A perspective on renewable bioenergy from photosynthetic algae as feedstock for biofuels and bioproducts. Algal Res., 24: 261-264.

Lee, J. Y.; Yoo, C.; Jun, S. Y.; Ahn, C. Y. and Oh, H. M. (2010). Comparison of several methods for effective lipid extraction from microalgae. Bioresour. Technol., 101(1):S75-S77.

Lundquist, T. J.; Woertz, I. C.; Quinn, N. W. T. and Benemann, J. R. (2010). A realistic technology and engineering assessment of algae biofuel production. Energy Biosciences Institute, pp. 1-178.

Malik, S.; Shahid, A.; Haider, M. N.; Amin, M.; Betenbaugh, M. J.; Mehmood, M. A. and Boopathy, R. (2022). Prospects of multiproduct algal biorefineries involving cascading processing of the biomass employing a zero-waste approach. Curr. Pollut. Rep., 8(2): 147-158.

O'Hagan, D. T. and Fox, C. B. (2015). New generation adjuvants–from empiricism to rational design. *Vaccine*, *33*: B14-B20.

Orsi, E.; Claassens, N. J.; Nikel, P. I. and Lindner, S. N. (2021). Growth-coupled selection of synthetic modules to accelerate cell factory development. Nat. commun., 12(1): 5295.

Posadas, E.; Alcántara, C.; García-Encina, P. A.; Gouveia, L.; Guieysse, B.; Norvill, Z. and Muñoz, R. (2017). Microalgae cultivation in wastewater. In Microalgae-based biofuels and bioproducts. Woodhead Publishing, pp. 67-91.

Posten, C. (2009). Design principles of photo-bioreactors for cultivation of microalgae. Eng.Life Sci., 9(3): 165-177.

Qaim, M. (2016). GM crop regulation. In Genetically Modified Crops and Agricultural Development. Springer, New York: Palgrave Macmillan US, pp. 109-134.

Quinn, J. C.; Smith, T. G.; Downes, C. M. and Quinn, C. (2014). Microalgae to biofuels lifecycle assessment—Multiple pathway evaluation. Algal Res., 4: 116-122.

Radakovits, R.; Jinkerson, R. E.; Darzins, A. and Posewitz, M. C. (2010). Genetic engineering of algae for enhanced biofuel production. Eukaryot. cell, 9(4): 486-501.

Rednikova, T. V. (2022). Legal Regulation of Commercial Cultivation of Genetically Modified Crops: Foreign Experience. Sel'skoe Chozjajstvo, *2*: 1–12.

Ren, L. J.; Huang, H.; Xiao; A. H.; Lian, M.; Jin, L. J. and Ji, X. J. (2009). Enhanced docosahexaenoic acid production by reinforcing acetyl-CoA and NADPH supply in Schizochytrium sp. HX-308. Bioprocess biosyst. Eng., 32: 837-843.

Richardson, J. W.; Johnson, M. D. and Outlaw, J. L. (2012). Economic comparison of open pond raceways to photo bio-reactors for profitable production of algae for transportation fuels in the Southwest. Algal Res., 1(1): 93-100.

Rosales Calderon, O.; Tao, L.; Abdullah, Z.; Talmadge, M.; Milbrandt, A.; Smolinski, S. and Payne, C. (2024). Sustainable aviation fuel state-of-industry report: hydroprocessed esters and fatty acids pathway (No. NREL/TP-5100-87803). National Renewable Energy Laboratory (NREL), Golden, CO (United States).

Ryckebosch, E.; Bruneel, C.; Termote-Verhalle, R.; Goiris, K.; Muylaert, K. and Foubert, I. (2014). Nutritional evaluation of microalgae oils rich in omega-3 long chain polyunsaturated fatty acids as an alternative for fish oil. Food chem., 160: 393-400.

Sami, M.; Mohammad, D. A.; Sallam, A. E. D. and Mohammed, S. Z. (2016). Seed rearing of *Ruditapes decussatus* (Bivalvia: Mollusca) using two culture techniques. Azhar Bull Sci, *27*(2): 51-66.

Sami, M.; Ibrahim, N. K. and Mohammad, D. A. (2020). Effect of probiotics on the growth performance and survival rate of the grooved carpet shell clam seeds, Ruditapes decussatus,(Linnaeus, 1758) from the Suez Canal. Egypt. J. Aquat. Biol. & Fish, *24*(7-Special issue): 531-55.

Sami, M.; Ahmed, F.; Temraz, T. A. and Ali, A. A. (2025). Ecological study on seaweed diversity in Suez, Hurghada and Marsa Alam, Red Sea, Egypt. *BMC Ecol. Evol.*, *25*(1): 1-18.

Sanches, P. H. G.; de Melo, N. C.; Porcari, A. M. and de Carvalho, L. M. (2024). Integrating molecular perspectives: strategies for comprehensive multi-omics integrative data analysis and machine learning applications in transcriptomics, proteomics, and metabolomics. Biology, 13(11): 848.

Sarker, N. K. and Kaparaju, P. (2024). Microalgal Bioeconomy: A Green Economy Approach Towards Achieving Sustainable Development Goals. Sustainability (2071-1050), 16(24):11218.

Sathesh-Prabu, C., Shin, K. S., Kwak, G. H., Jung, S. K. and Lee, S. K. (2019). Microbial production of fatty acid via metabolic engineering and synthetic biology. Biotechno. Bioprocess Eng., 24: 23-40.

Schenk, P. M.; Thomas-Hall, S. R.; Stephens, E., Marx, U. C.; Mussgnug, J. H.; Posten, C. and Hankamer, B. (2008). Second generation biofuels: high-efficiency microalgae for biodiesel production. Bioenergy res., 1: 20-43.

Seo, K. and Oronoz, S. (2023). Natural leaf-inspired solar water splitting system. Appl. Catal. B-Environ., 322: 122086.

Shin, S. E.; Lim, J. M.; Koh, H. G.; Kim, E. K.; Kang, N. K.; Jeon, S. and Jeong, B. R. (2016). CRISPR/Cas9-induced knockout and knock-in mutations in Chlamydomonas reinhardtii. Sci. rep., 6(1): 27810.

Srivastav, P. P. and Karunanithi, S. (Eds.). (2024). Emerging Methods for Oil Extraction from Food Processing Waste. CRC press (Taylor &Francis group), 233pp.

Taher, H.; Al-Zuhair, S.; Al-Marzouqi, A. H.; Haik, Y.; Farid, M. and Tariq, S. (2014). Supercritical carbon dioxide extraction of microalgae lipid: process optimization and laboratory scale-up. J. Supercrit. Fluids, 86: 57-66.

Tran, D. P. H.; You, S. J.; Bui, X. T.; Wang, Y. F. and Ramos, A. (2024). Anaerobic membrane bioreactors for municipal wastewater: Progress in resource and energy recovery improvement approaches. J. Environ. Manage., 366: 121855.

Ugwu, C. U.; Aoyagi, H. and Uchiyama, H. (2008). Photobioreactors for mass cultivation of algae. *Bioresour. Technol., 99*(10): 4021-4028.

Wang, H. M. D.; Li, X. C.; Lee, D. J. and Chang, J. S. (2017). Potential biomedical applications of marine algae. Bioresour. technol., 244: 1407-1415.

Wang, J. H.; Yang, H. Z. and Wang, F. (2013). Mixotrophic cultivation of Scenedesmus sp. as biodiesel feedstock. Adv. Mater. Res., 777: 268-273.

Wang, S. K.; Stiles, A. R.; Guo, C., and Liu, C. Z. (2015). Harvesting microalgae by magnetic separation: A review. Algal Res., 9: 178-185.

Wijffels, R. H., and Barbosa, M. J. (2010). An outlook on microalgal biofuels. science, 329(5993): 796-799.

Xia, S.; Lin, J.; Sayanjali, S.; Shen, C. and Cheong, L. Z. (2024). Lipase-catalyzed production of biodiesel: a critical review on feedstock, enzyme carrier and process factors. Biofuels, Bioprod. Biorefin., 18(1): 291-309.

Xu, P.; Shao, S.; Qian, J.; Li, J.; Xu, R.; Liu, J. and Zhou, W. (2024). Scale-up of microalgal systems for decarbonization and bioproducts: Challenges and opportunities. Bioresour. Technol., 130528.

Xue, J.; Niu, Y. F.; Huang, T.; Yang, W. D.; Liu, J. S. and Li, H. Y. (2015). Genetic improvement of the microalga *Phaeodactylum tricornutum* for boosting neutral lipid accumulation. Metab. Eng., 27: 1-9.

Yang, H.; Yu, B.; Xu, X.; Bourbigot, S.; Wang, H. and Song, P. (2020). Lignin-derived bio-based flame retardants toward high-performance sustainable polymeric materials. Green chem., 22(7): 2129-2161.

Yang, J.; Xu, M.; Zhang, X.; Hu, Q.; Sommerfeld, M. and Chen, Y. (2011). Life-cycle analysis on biodiesel production from microalgae: water footprint and nutrients balance. Bioresour. technol., 102(1): 159-165.

Zhang, Y.; Adams, I. P. and Ratledge, C. (2007). Malic enzyme: the controlling activity for lipid production? Overexpression of malic enzyme in Mucor circinelloides leads to a 2.5-fold increase in lipid accumulation. Microbiology, 153(7): 2013-2025.

Zhu, L.; Li, S.; Hu, T.; Nugroho, Y. K.; Yin, Z., Hu, D. and Hiltunen, E. (2019). Effects of nitrogen source heterogeneity on nutrient removal and biodiesel production of mono-and mix-cultured microalgae. Energy Convers. Manag., 201: 112144

Zittelli, G. C.; Rodolfi, L.; Biondi, N. and Tredici, M. R. (2006). Productivity and photosynthetic efficiency of outdoor cultures of *Tetraselmis suecica* in annular columns. Aquaculture, 261(3): 932-943.