Review Article

The Lipid Extraction Methods from Algae for Biofuel Production: A Review of Recent Developments and Future Prospects

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Abstract | Microalgae are among the most promising biological sources for biofuel production because they can rapidly accumulate lipids, exhibit high specific growth rates, and can be cultured without competing with food crops. Biodiesel from algae production primarily involves oil extraction and conversion into fatty acid esters via esterification or chemical or enzymatic transesterification. Recent years have seen significant progress in this field, with the addition of innovative, high-performance homogeneous and heterogeneous catalysts, as well as nano- and enzymatic catalysts, which enhance conversion efficiency and minimize the process's environmental footprint. Additionally, new oil extraction techniques have been developed using biocompatible solvents (e.g., dimethyl ether and supercritical carbon dioxide) in conjunction with innovative intensification methods (e.g., ultrasound, microwave, and pressurized fluid extraction), resulting in shorter processing times and improved recovery. This study assesses recent progress in various algal lipid extraction technologies and their conversion into biofuel, considering productivity-related aspects such as algae type/cultivation conditions/lipid content/ biomass pre-treatment. A bulk of these techniques is thoroughly discussed, including genetic engineering and new refinements in biotechnological methodologies, leading to enhanced lipid accumulation within algal cells and improved ultimate biofuel outcome. The results indicate that coupling cell disruption techniques with green solvents and intensification strategies can considerably enhance process efficiency and the quality of the harvested products. Therefore, additional research and development are needed to realize economical, sustainable biofuel production from algae.

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Introduction

Microalgae are a promising group of microorganisms for biodiesel and biofuel production, as they have higher oil productivity and growth rates than other biomass feedstocks and do not require arable land used for food crops. In particular, algae are used for biofuel production via esterification, in which oils obtained from algae are converted primarily to methyl or ethyl esters (biodiesel) using chemical or enzymatic methods. Recent advances in esterification from improved catalyst selection and extraction methods to genetic engineering to boost algae fat content have enabled the technology to be refined in recent years. There are still some hurdles related to cost, process efficiency, and the feasibility of larger-scale production. Herein, we intend to present recent and valuable information on biofuel extraction and production from algae, along with selected features of the latest studies, in table and figure format. (Context: These data are for cutting-edge computational display units developed in laboratories at some of the best universities in the world (Farouk *et al*., 2024; Zhang *et al*., 2022; Wang *et al*., 2024), while real-world performance is also achievable through training at assembly line scale, but only with two less performant models (Sundaram *et al*., 2023; Ye *et al*. Recent studies on the industrial production of polyunsaturated fatty acids from algae show that improved extraction is always associated with a combination of techniques: cell cleavage (via high-pressure homogenization, pulsed electrical discharge, or enzymes), and green solvents such as ethanol and DME; intensive techniques such as ultrasonic and microwave extraction; and electrofluidic supercritical extraction. The techniques are aimed at acquiring high-quality components rich in EPA and DHA (Chen *et al*., 2023; Zhang *et al*., 2022).

This article serves as a comprehensive and up-to-date scientific literature review of the latest methodologies for extracting and converting microalgal lipids into biofuels. In particular, the study explores recent advances in esterification and ester exchange for biodiesel production. It further aims to evaluate the important determinants influencing biofuel productivity from algae, including algal species, growth environmental factors, lipid content, and extraction and processing techniques. It also serves to review modern extraction techniques, which may include green solvents and intensive methods (e.g., ultrasound, microwave, or supercritical fluid extraction), discussing their advantages and disadvantages as well as their suitability for industrial manufacturing. Lastly, this research aims to identify future research trends that will help improve production efficiency, cost-effectiveness, and environmental sustainability in the algae-based biofuel sector.

Algae oil esterification: Recent advances

In the last few years, there has been great advancement in esterification technologies. To enhance conversion efficiency and reduce environmental burden, homologous, heterologous, nano-, and enzymatic catalysts have been engineered (Farouk *et al*., 2024; Sundaram *et al*., 2023; Song *et al*., 2024; Nabgan *et al*., 2022). Moreover, higher conversion rates of fatty acids to biodiesel have been shown in the literature, 95% under favourable conditions (Farouk *et al*., 2024).

Factors that influence the biodiesel production from algae

Several factors impact lipid accumulation, including algae type; lipid content; cultivation conditions (lighting and carbon dioxide concentration); extraction methods; and oil pre-treatment (Zhang *et al*., 2022; Wang *et al*., 2024; Yu *et al*., 2024). Genetic engineering is another way to increase intracellular lipid accumulation significantly (Wang *et al*., 2024; Song *et al*., 2024; Je and Yamaoka, 2022).

Extraction methods and auxiliary technologies (Algal lipid extraction)

To date, novel approaches to lipid extraction have been developed, including the use of non-toxic solvents (e.g., dimethyl ether) and technologies such as ultrasound and enzyme-assisted appliances that enhance oil recovery and efficiency and can be less energy intensive (Wang *et al*., 2024; Tong *et al*., 2022). This review highlights contemporary techniques for algal lipid extraction, including tables showing working conditions and advantages/disadvantages, along with other more recent references.

Enhanced lipid extraction with solvents (modified folch/bligh and dyer methods)

Time-honoured methods such as chloroform–methanol, Bligh and Dyer, and Folch are the standards. In contrast, new research aims to replace or reduce the use of toxic solvents and to combine them with physical therapies (e.g., sonication and vigorous mixing) to enhance lipid separation from cell walls (Chen *et al*., 2023; Zhang *et al*., 2022) (Table 1).

Ultrasonic extraction (UAE)

Ultrasonic extraction employs acoustic vents that rupture the cell wall, thereby accelerating lipid transfer into the solvent. Recent studies on oilseeds and algae have shown that it improves yield, reduces extraction time, and lowers solvent consumption (especially with green solvents) (Zhang *et al*., 2022). Table 2 algal lipid extraction in the UAE: common applications.

Table 1: *Examples of improved solvent extraction in algae.*

Modified technology	Algae type/ strain	Status	Solvent/ System	Fat efficiency/ yield	Pre-treatment requirements	Key Features	Key restrictions	References
Bligh and Dyer solvent-enhanced	Several microalgae for PUFA production	Partial dried	MeOH + less toxic solvents	yields comparable to or higher than the original protocol	Light grinding/ drying.	Reducing solvent toxicity while maintaining efficiency	Relative drying is still required.	(Chen *et al.*, 2023; Zhang *et al.*, 2022)
MeOH/alternative organic solvents system for the separation of ω3.	EPA/ DHA-rich microalgae	Dried	MeOH + n-hexane/ EtOAc	Improved extraction of free and polar PUFAs	Mechanical cell fragmentation	Better separation of PUFA-rich fractions	Multi-step, cost-effective solvent separation	(Chen *et al.*, 2023)

Table 2: *Representative UAE applications in algal lipid extraction.*

Algae type	Bulk state	Solvent used	Typical sonication conditions (power/ time/frequency)	Fat yield (compared to conventional methods)	Impact on PUFA quality	Main advantages	Limitations/ challenges	Ref.
Nannochloropsis sp.	Dried	ethanol or an alcoholic mixture.	Medium power (≈200–400 W), 10–30 minutes.	.2–1.5 greater than Soxhlet/ methanol.	Good EPA retention.	Reduced time and solvent, integrated.	Precise control to prevent oxidation	(Chen *et al.*, 2023; Zhang *et al.*, 2022)
Chlorella sp.	Semi hydrated	EtOH/ Water.	Typical frequency (20–40 kHz).	Similar yields with shorter time.	Acceptable fatty acid quality.	Useful for not fully dried mass.	Laboratory-to-industry grade	(Zhang *et al.*, 2022)

Table 3: *Pressurised fluid extraction and MAE application in algal lipids.*

Technique	Algal	type/ application	Sample condition Solvent/ phase	Typical T/P.	Yield/improvement versus Soxhlet or classical methods	Impact on PUFA/stability	Main advantages	Main limitations	References
Thermal MAE	General oil microalgae	Dried	Alcohol/ water	120–200 °C (short).	Yields may exceed 70% in much shorter times.	Risk of oxidation at high temperatures.	Accelerates the process; can be integrated with conversion.	Requires specialized reactors and precise control	(Chen *et al.*, 2023; Zhang *et al.*, 2022)
Pressurized Liquid Extraction (PLE)	PUFA rich microalgae	Partially dried	Food solvent (EtOH)	Moderately high temperature (≈100–200 °C), high temperature (P)	Yields comparable to or higher than Bligh and Dyer.	Good PUFA structure retention.	Food solvent use, short processing time	Low capital investment, high-pressure operation	(Chen *et al.*, 2023)

Microwave extraction (MAE) and pressurized fluid extraction

Then, the material and liquid mixture is uniformly heated in a microwave to increase internal pressure, which causes the breaking of cell walls. MAE (Microwave-Assisted Extraction) is an advanced technique for intensive material extraction that improves algal production and effectively reduces processing time compared with conventional thermal methods (Chen *et al.*, 2023; Zhang *et al.*, 2022). Table 3 microwave assisted extraction and pressurised fluid extraction in algal lipid production.

Supercritical CO_2 extraction (SFE)

SFE (supercritical CO_2 extraction) is one of the greenest methods for extracting materials and is commonly used to extract algal oils and pigments at low temperatures, yielding very pure extracts (Tzima *et al.*, 2023). Recent reviews have shown that the selectivity of oils, fatty acids, and carotenoids can be adjusted by pressure and temperature, or by the addition of auxiliary solvents such as ethanol (Tzima *et al.*, 2023). Table 4 the use of supercritical CO_2 in lipid extraction from algae.

Table 4: *In this study: Supercritical carbon dioxide for lipid extraction from algae.*

Type of algae/target compounds.	status	Typical CO_2 (P, T) conditions	Presence of Co-solvent	Main target (lipids/carotenoids/fatty acids)	Typical yield/extraction	Main advantages	Limitations and challenges	Ref.
Microalgae (Nannochloropsis, Chlorella)	dried ground	25–40 MPa، 40–60 °C	Predominantly EtOH.	Total fats + PUFAs.	Good yields with high purity.	Virtually solvent-free extract, suitable for food and pharmaceutical use.	processing cost, lower efficiency with very wet mass	(Tzima *et al.*, 2023)
Haematococcus, Dunaliella (pigments + lipids)	Dried/ finely ground	May reach 70 MPa and higher temperatures.	EtOH or not.	Astaxanthin/ carotenoids + conjugated lipids.	High recovery of pigments and lipids.	High selectivity under controlled pressure/temperature.	Pre-grinding/ pre-treatment is necessary to improve permeability.	(Tzima *et al.*, 2023)

Table 5: *Wet algal lipid extraction with DME: Application.*

Algae type.	Water content in bulk	DME system configuration	Extraction time	Fat extraction efficiency/ FAME (typical)	Pre/post treatment steps	Key advantages	Safety/ engineering limitations or challenges	Reference
High-moisture microalgae (Nannochloropsis, Chlorella)	≥80٪ water	Pure DME or DME + 8% EtOH/acetone	≈30 ≈30 minutes	Can achieve ≈26–30% crude fat and ≈50–55% FAME in the first cycle	No need for pre-drying or pre-cell breaking	Significantly reduced energy consumption, simultaneous extraction and dehydration, and a relatively food-safe solvent	Requires pressurized equipment and safe management of flammable gas	(Wang *et al.*, 2024)

Table 6: *Extractive for biodiesel production from algal oils.*

Algae/ Material type	Catalyst type	Operating conditions.	Conversion rate (%)	Reference
Tall oil fatty acids	H_2SO_4	55°C, oil:methanol ratio = 15:1, time = 1 hour	96.76	(Farouk *et al.*, 2024)
Waste cooking oil (As a comparative example)	NaOH	40°C, oil:methanol ratio = 9:1, time = 2 hours	98.22	(Farouk *et al.*, 2024)
Nannochloropsis sp.	Heterocyclic/enzymatic catalyst	Various conditions according to the study	Up to >90%	(Ye *et al.*, 2024)
Chlorella vulgaris	Enzymatic/gene catalyst	Genetic modification + improved environmental conditions	Fat almost doubles	(Je and Yamaoka, 2022)

Liquid DME (Dimethyl Ether) for wet mass extraction

Liquid DME has also been well explored as a non-toxic, environmentally friendly solvent for extracting lipids and active compounds from high-water-content microalgae (without drying), with much lower energy consumption than conventional extraction methods (Wang *et al.*, 2024). In verses, though, it has an extremely low boiling point, making it easy to remove the solvent; it has excellent wetting power, can permeate the wet mass, and extracts some water during the extraction process. Table 5 DME applications in w*et al*gal lipid extraction.

Challenges and real-world applications

Although technology has advanced, high costs and scalability remain significant barriers in the industry (Wang *et al.*, 2024; Sundaram *et al.*, 2023). Algal biodiesel is a sustainable alternative to fossil fuels and can contribute to carbon emission reductions, but it is still in its infancy (Ye *et al.*, 2024; Yu *et al.*, 2024). Table 6 illustrates the Extractive for biodiesel production from algal oils.

Discussion

Recent studies have shown that the use of advanced catalysts for esterification, combined with the latest extraction methods, has improved algal biodiesel production, making it more efficient and cheaper than ever before (Farouk *et al.*, 2024; Sundaram *et al.*, 2023;

Wang *et al.*, 2024). Nevertheless, the innovation needs to continue to lower production costs and energy consumption, as well as to improve the extraction and pre-treatment of algae (Zhang *et al.*, 2022; Yu *et al.*, 2024). By using genetic engineering and modern biotechnologies, it is possible to achieve substantial increases in intracellular lipid content and, as a result, the final biofuel yield (Wang *et al.*, 2024; Song *et al.*, 2024; Je and Yamaoka, 2022). However, the most critical issue is still to upscale these technologies to industrial scale while maintaining economic viability and environmental sustainability. Supercritical CO_2 in combination with liquid DME is regarded as the state of the art in modern green technologies for algal lipid extraction (Tzima *et al.*, 2023; Wang *et al.*, 2024). Methods such as UAE, MAE, and PLE exhibit stronger extraction capabilities than mild processing conditions and can thus be coupled with less hazardous solvents (Chen *et al.*, 2023; Zhang *et al.*, 2022). The most appropriate technology depends on the form of algal mass (wet/dried), the target product type (megafuel or high-value food-grade PUFAs), and the potential for investment and industrial operations.

Conclusion

Recent studies identified microalgae as a potent and sustainable biofuel feedstock, with high protein content at high volumes in the structure, grown in medium miscible with no food safety concerns (Dunaliella Salina, for instance). Esterification techniques have modernized, and the design of chemical, enzymatic, or nanomaterial activators has increased the efficiency of oil biofuel conversion while achieving high conversion yields under specific operating conditions. More modern lipid extraction techniques, including ultrasound-assisted, microwave-assisted, supercritical fluid extraction, and green solvents, have also shown remarkable efficiency in improving the purity of extracted lipids and in reducing energy and time consumption compared to traditional methodologies. Moreover, the use of genetic modification techniques has improved lipid accumulation. Nevertheless, there are some major challenges, including high production costs and the transferability from laboratory experiments to full-scale industrial operations. Hence, the destiny of this domain is contingent on developing integrated processes that synergistically combine effective cell destruction, ultraclean isolation, and proficient chemical transesterification, with optimized industrial process design, to achieve economic and environmental feasibility. Further research in this area will maintain algae's respectable status as an essential source of renewable energy and drive the transition to more stable energy systems.

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Novelty Statement

This review provides an updated and comprehensive evaluation of recent advancements in microalgae-based biofuel production, with particular emphasis on innovative lipid extraction and transesterification techniques. The study integrates recent developments in nanomaterial catalysts, microwave- and ultrasound-assisted extraction, supercritical fluid technologies, and genetic modification approaches aimed at enhancing lipid productivity and biofuel conversion efficiency. Unlike conventional reviews, this work critically discusses the techno-economic and industrial scalability challenges while proposing integrated processing strategies to improve the environmental and economic feasibility of sustainable algal biofuel production systems.

Author's Contribution

Husam Talib Hamzah: contributed to the conceptualization of the study, literature review, data analysis, and manuscript drafting. Veluru Sridevi: participated in the supervision, scientific revision, and interpretation of the technical aspects related to biofuel production and renewable energy systems. Fouad Hussein Ali: contributed to manuscript editing, validation of scientific content, and final review of the paper. All authors read and approved the final manuscript.

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