HIGH SCHOOL EDITION
Journal of Student Research

Volume 13 Issue 4 (2024)

What are the Key Technological and Logistical Challenges in Harvesting and Processing Algae for Biofuel Production, and How Can They Be Overcome?

Jionghao Wu[1] and Alexandra E. Pagano[#]

[1]Pomfret School, Pomfret, CT, United States
[#]Advisor

ABSTRACT

Rising fossil fuel consumption worsens ecological destruction and causes changes to renewable energy sources. Microalgae for biodiesel production can emerge as a sustainable solution by bypassing the constraints of land and water associated with traditional biofuels. Cultivation has changed to incorporate optimized photobioreactors and wastewater synergies, while harvesting and lipid extraction techniques have improved to lower environmental footprints through electro-coagulation-flocculation and supercritical CO2 extraction, among others. These technological strides are summarized in this review which shows how selective breeding, genetic engineering, and integrated biorefinery approaches enhance the economic feasibility of algae-based biofuel. An interdisciplinary approach is required to magnify algae's role in the future of sustainable energy. Research along with policy support has been driving the progression of microalgae biofuels toward carbon neutrality which positions algae as a global player in the quest for energy independence.

Introduction

Fossil fuel consumption has increased tremendously since 1950 due to human activity, which has led to massive depletion of fossil energy reserves and adverse environmental impacts.[1] The need for fossil fuels is only predicted to grow by as much as 40% from 2010 to 2040.[2] Carbon dioxide emissions from fossil fuel combustion account for the most significant percentage (77%) of total U.S. greenhouse gas emissions.[1] Under the Paris Agreement, an agreement between 195 nations, including the United States, the United States promised (in 2015) to reduce greenhouse gas emissions by 26-28% by 2025 compared to 2005.[1] To achieve these goals there must be a worldwide shift towards renewable power sources with global carbon neutrality being aimed at.

Switching from traditional fuels such as petroleum and diesel to biofuels is necessary to reduce environmental pollution and enhance sustainable agriculture. The two main biofuels are ethanol and biodiesel, which are known to be environmentally friendly.[3] Biodiesel is considered an attractive alternative to traditional diesel when produced from renewable feedstock, such as vegetable oils or animal fats. Indeed, its components consist predominantly of long-chain fatty acid esters made from methanol or ethanol, in contrast to traditional diesel, which is made of crude oil.[3] The interest in biodiesel among international researchers mainly comes from its potential to significantly reduce reliance on fossil fuels and combat pollution.[3] Depending on the feedstock type, biodiesel development can be divided into three stages. The first generation used edible crops such as corn and soybeans, which have been highly debated due to their need for large tracts of land and water that could have been used for growing food.[2] This led to the second-generation biodiesel that used lignocellulosic feedstock like straw, thereby reducing some concerns associated with the first-generation and bringing about others about cost and energy efficiency.[2,3] Thirdly, third-generation biodiesel from microalgae boasts a high lipid content, requires little land occupation, and does not interfere with food supplies.[2,3] Microalgae's ability to survive in diverse environments alongside a short growth cycle makes it appropriate for biofuel production use as a raw material.[3] This era marks a significant stepping stone in tapping carbon resources from the natural environment into our energy systems, advancing us toward sustainable energy independence and environmental restoration.

Therefore, algal biofuels are a big step forward in pursuing sustainable energy solutions. The benefits of microalgae, such as fast growth speed, excellent biomass productivity, and ability to grow in non-arable lands, have made them an ideal replacement for conventional biofuel sources.[4] However, the large-scale adoption of microalgae as a feedstock is challenging. Commercializing algal biofuel involves overcoming significant technological and logistical challenges, from efficient cultivation and harvesting to effective processing and conversion into viable fuel.[3] To address these challenges, an interdisciplinary approach that incorporates biology, chemistry, and engineering must be adopted to maximize the full potential of algae in shaping tomorrow's energy landscape. In this regard, this study aims to dissect the problems above by exploring how innovative strategies can assist in optimizing production processes, leading to reduced greenhouse gas emissions and a more sustainable, eco-friendly future energy scenario globally.

Parameters for Biofuel Production

The field of algae biofuel production is growing to create renewable energy by processing algal biomass. This complicated process encompasses culturing, harvesting, and lipid extraction which is demonstrated in Fig 1; each of these steps poses specific challenges, even though certain conditions must be optimized to achieve high yields to be economically viable as biomass.

Cultivation

The first stage in biofuel production is cultivation, where microalgae are cultured under suitable aquatic conditions. Algae can be grown in two primary systems: open ponds and closed photobioreactors.[5] Open ponds, which are cost-effective and easy to construct, are large shallow pools using natural sunlight as the light source.[5] However, there are disadvantages, such as the threat of contamination from other microorganisms, evaporation, and less control of environmental factors.[6] Conversely, closed photobioreactors are controlled systems typically made up of transparent tubes or containers where light intensity, temperature, CO2 levels, and nutrient supply can be adjusted accordingly.[5] Photobioreactors provide high biomass yield and prevent contamination but require more extraordinary operating expenses than open ponds.[6]

Light intensity, sun quality, CO2 concentration, and availability of nutrients affect growing algae at any given time.[3] Light is crucial for photosynthesis, which involves converting light energy into chemical energy in algae. However, too much light can result in photooxidative harm, leading to reduced growth rates.[5] Algae also need water; while freshwater is commonly used, some species grow best in brackish or seawater, relieving strain on freshwater resources.[3] The optimal ratios of water and sunlight required vary depending on the type of algae species involved and environmental conditions.[5] CO2 also improves photosynthetic efficiency, thus significantly enhancing growth. Besides containing CO2 and improving algal growth, new technologies like flue gas involve additional environmental benefits like carbon sequestration.[7]

The salinity required for the growth of microalgae depends on its type. Some types of microalgae can tolerate higher salinity levels than others, whereas freshwater species require the lowest salinity. In order to adjust the salinity, marine algae may be treated with common salts such as NaCl and sodium sulfate (Na2SO4). However, excessive amounts of these substances can inhibit their growth. Carbon, oxygen, hydrogen, nitrogen, phosphorus, and potassium are some of those elements considered important for microalgal nutrition. The first three come from the water and air. At the same time, the latter three are supplied through a culture medium, which is a nutritive substance, such as an agar gel or liquid medium, in which cultures of bacteria, fungi, animal cells, or plant cells are grown [3]. Another important factor affecting enzyme activity, nutrient availability, and toxicity is pH. When microalgae photosynthesis, microalgal cells raise their surroundings' alkalinity levels, altering their nutritional requirements alongside those necessary for supporting growth [3].

Lipid Accumulation

The lipid accumulation in microalgae is greatly influenced by various culture conditions such as nutrients, salinity, light, and temperature, which all play crucial roles in the biological activity of these organisms.[8]

Nutrients: Nitrogen is necessary for cell structure in microalgae. Nitrogen also contributes to protein synthesis, which is used as material for making amino acids, nucleic acid enzymes, and photosynthetic pigments, among others.[9] All components at the cellular level depend directly on their availability, making it one key factor affecting their functions.[9] Phosphorus is an essential element required by all living cells mainly because it is involved in metabolic processes associated with growth, such as respiration, photosynthesis, etc.[10] In addition to this function, phosphorus also takes part in energy transfers within cells during signal transductions while serving as a building block for the synthesis of macromolecules like DNA, RNA, proteins, etc.[10]

Salinity: Lipid synthesis can be affected by altering salt concentrations, which either increase or decrease microbial resistance and influence growth rates among microalgal cells.[11] When osmotic pressures rise inside due to high slime environments, it changes the flexibility of the outer membrane, thus enabling them to withstand more stressors like pathogens than usual, leading to higher storage levels being recorded.[11]

Light: Microalgae require light because they are phototrophic organisms; they have chlorophyll pigments that enable them to trap photons responsible for photosynthesis.[12] The most appropriate wavelength range over which absorption occurs falls between 400 nm -700nm, taking up approximately 43% of solar radiation intensity.[12] Depending on its intensity and quality, different types or species may respond differently through growth rates achieved and lipid-produced quantities attained.

Temperature: Metabolic pathways within microalgae are most likely to be influenced by alterations caused by fluctuations in temperature, which can result in different changes shown through various lipid production levels.[13] Growth efficiency happens when high and low temperatures induce stress, affecting growth rate and final lipid composition quality.[13]

Harvesting

As soon as the algae have reached a certain density, they are harvested for oil extraction. This stage is difficult to achieve without adequate algal density or yield.[2] Common methods of harvesting include centrifugation, gravity sedimentation, and flocculation.[2] Centrifugation is effective but energy-demanding and sometimes uneconomical when it comes to large-scale operations.[3] Gravity sedimentation relies on the natural sinking of cells over time; however, it is not applicable to all microalgae which do not settle easily. Flocculation entails the use of chemicals to make algal cells stick together so as to be separated easily though this may pose ecological and safety risks.[2]

Pre-Processing and Lipid Extraction

The last step is to isolate the lipids from collected dried algae that can later be converted into biofuel. However, pre-processing, the action of breaking the algae's cell wall, which is hard and thick, has to happen first. The wall's strength and thickness dictate the algae cell's ability to resist mechanical fragmentation. [3] Moreover, factors like salinity, nutrients, and UV light will impact the properties of the microalgae cell wall. There are two main types of extractions: mechanical and chemical methods.[6] Mechanical extraction techniques involve pressing and physically squeezing out the oil from the algal cell.[6] The process is simple but may not remove all the oil available, particularly in cases where there are rigid cell walls made up of cellulose or chitin.[6] Chemical extraction utilizes solvents such as hexane or methanol to dissolve lipids found in algae. [3] While chemical extraction has been found to yield more quantities than mechanical processes, it involves dealing with dangerous substances, and proper disposal systems need to be put in place. [3] A relatively new technique known as supercritical fluid extraction, which uses carbon dioxide under high pressure and temperature, has shown higher efficiency and increased environmental safety over traditional chemical extractants.[14] However, buying equipment for this purpose is expensive, and energy cost requirements are high, thereby limiting its applications on a large scale.[14]

Every phase linked with algal biofuel production entails unique difficulties. Various environmental parameters must be manipulated when cultivating the organisms to achieve high growth rates and lipid yields.[3] Harvesting should be efficient and economical enough to gather algal cells without unjustifiably raising prices.[2] Lastly, oil extraction ought to separate lipids from biomass sustainably and in an environmentally friendly manner.[6]
Researchers and industry leaders have developed and refined a range of methods to optimize the cultivation, harvesting, and oil extraction operations aimed at tackling the technological and logistical obstacles associated with algae biofuel production. These strides are critical in the pursuit of sustainable energies as they ensure that algae-based biofuel can be scaled up economically.

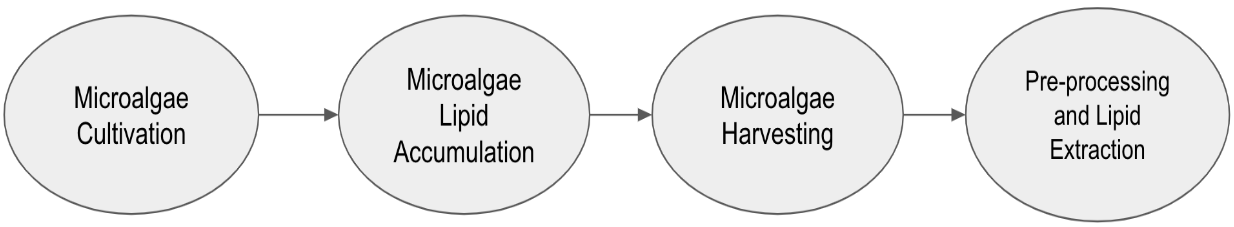

Figure 1. Production process of microalgal biodiesel.

Microalgae Cultivation Technologies

Optimized Photobioreactor Design

Closed Photobioreactor (PBR) systems have become a point of reference for algal cultivation innovation with design optimization to maximize light exposure, quickly adjust temperature, CO2 levels, and nutrient supply, and prevent contamination.[15] PBR technology has advanced through the engineering of light paths by shortening the light reaches to zones that otherwise would be dark and developing materials that increase surface area to volume ratios, thereby enabling better penetration of light with less dark zones where photosynthesis is restricted. The studies have shown that integrating PBRs with more efficient gas exchange mechanisms and elements diffusing lights can support higher cell densities and productivity rates.[15] These advancements include automated control systems for maintaining optimum conditions throughout the growth cycle – temperature, pH, and CO2 levels.[15]

Wastewater Utilization

The entwining of algae farming into wastewater treatment provides a two-way benefit: an economical source of nutrients for algae growth in nutrient-rich wastewater and bioremediation by algae.[5] According to recent research, some microalgae species can thrive in wastewater media by assimilating nitrates, phosphates, and other organic compounds, reducing reliance on chemical fertilizers.[5] This method also reduces operational expenses and aligns with sustainable development goals by assisting in waste management. On the other hand, algae can also be grown in industrial wastewater, which contains heavy metals and chemicals that are hard to digest compared to farm wastes, which have many organic nutrients from plants and animals. However, algae will be able to grow well in both types of wastewater. Moreover, fuel made from algae that applied the wastewater cultivation method can potentially lower the production cost of biofuels up to nearly 50%, improving their cost-competitiveness with conventional petroleum-based alternatives.[16]

CO2 Sequestration via Flue Gas

Recent studies have examined using industrial flue gasses as carbon sources for cultivating microalgae. Direct CO2 input from flue gasses to algal cultures can significantly increase growth rates and lipid accumulation, essential for biofuel production processes.[5] Innovations in gas delivery systems ensure that CO2 is dispersed uniformly across the medium, leading to higher sequestration rates and improved biomass yield.[5]

Hybrid Cultivation Systems

Hybrid systems have been proposed to use both open ponds and PBRs. The systems usually begin with an open pond arrangement during the early stages of algal growth since operational costs are lower in this case.[5,17] This is followed by a transfer to a PBR when the culture is ready for final biomass production.[15,17] Such staging allows for cost-effective scaling of biomass production while ensuring that lipid accumulation occurs in the final growth stage under controlled and optimized conditions.[17]

LED Lighting Technologies

LED lighting has transformed indoor algal cultivation by providing a tailored spectrum light source, maximizing photosynthetic activities.[5,17] The ability to adjust intensity and wavelength characteristics makes LED lights suitable for algae exposures to optimal light spectra irrespective of geographical or climate constraints.[17,5] Besides, LED systems consume less energy and have longer lives compared to traditional lighting systems, contributing towards reduced carbon footprint and decreased operational expenses.[17,5]

Selective Breeding and Genetic Engineering

Through selective breeding and genetic engineering, new horizons have been unlocked in cultivating strains of algae with enhanced biofuel production characteristics.[15] Researchers have developed algal strains better suited for biofuel applications through selection based on traits such as increased lipid content, faster growth rates, and resilience against environmental stressors.[17] Genetic engineering techniques further alter metabolic pathways to increase lipid accumulation, optimizing biofuel production.[17]

Microalgae Harvesting Technologies

Harvesting microalgae is complex. Therefore, there have been investigations to develop and improve new techniques to make this step more efficient and have a lower energy footprint.

Electro-Coagulation-Flocculation

This method is an excellent advancement in algae harvesting technology because it causes the coagulation of algal cells by applying an electrical current to the algae culture, which produces charged particles that facilitate subsequent flocculation and separation.[15] This helps reduce the energy cost of traditional chemical flocculation and minimizes the use of chemical coagulants, thus presenting a green alternative.[15]

Auto-Flocculation Induced by pH Shift

Research shows that some algae species are auto-flocculent, so manipulation of their culture media pH triggers their natural flocculation.[18] The approach depends on the physiology of these organisms and represents a sustainable way to harvest them without using chemical flocculants. Consequently, it not only saves money but also helps protect the environment. However, such an approach may work differently with various algal strains, which makes it less effective in multicultural environments.[15]

Foam Flotation

Foam flotation has been adapted for microalgae harvesting after being initially modeled from a technique widely used in the mineral processing industry.[3,18] In this method, air is introduced into the algal culture to produce foam, which entraps the algal cell on its surface.[15] It works well, especially for naturally hydrophobic or conditioned strains. The most crucial feature of foam flotation is its efficiency and scalability potential. Nevertheless, the requirement for specific surface properties of algae might limit its universality among different types.[15]

Magnetic Separation

Magnetic separation takes advantage of magnetism through additional magnetic nanoparticles that bind to algal cells, enabling them to be acted upon by magnetic forces when necessary.[18] All that needs to be done is applying a magnetic field to facilitate separation between biomass and medium. The rapidity of this method's separation, as well as the ability for nanoparticle recovery and reuse, have made many people interested in it.[18] However, despite these advantages, some drawbacks still exist, including high initial costs associated with nanoparticles and possible risks related to their complete retrieval or toxicity.[18]

Centrifugation Optimization

Centrifugation has been the standard method of algae harvesting, but it is very energy-consuming. [3]. Recent improvements in centrifugation protocols have included continuous-flow centrifuges that promise lower energy usage while maintaining high biomass recovery rates.[15] There is ongoing research aiming to optimize operational parameters such as rotor speed and flow rate to improve efficiency. Although these systems require more energy than batch centrifuges, which are known to be less efficient than them, they may still not meet sustainable power requirements.[15]

Gravity Settling Enhanced by Bio-Flocculants

Gravity settling refers to the process in which algae cells settle naturally [3]. It has been suggested that natural flocculants be introduced into the system to enhance this process. These flocculants are environmentally friendly because they can cause clumping without any adverse effects associated with synthetic polymers.[18] Various plant-based and microbial flocculants are being studied for their efficiency among algal species under different operation conditions. Although an eco-friendly alternative option, the effectiveness of this method largely depends on the specific properties of used flocculants as well as operational conditions, which might vary greatly.[15,18]

Lipid Extraction Technologies

Oil extraction from harvesting microalgae biomass is a crucial step in biofuel production. This stage has experienced significant technological development to increase efficiency and productivity and improve environmental sustainability. Some extraction methods include Supercritical Fluid Extraction (SFE), Ultrasonic-Assisted Extraction (UAE), Enzymatic Extraction, Microwave-Assisted Extraction (MAE), Solvent-Based Extraction Optimization, and Integrated Biorefinery Approaches.

Supercritical Fluid Extraction (SFE)

Supercritical CO2 extraction leads the pack regarding oil extraction technologies for its extraction efficiency and purity.[19] This method dissolves algae in supercritical CO2 so that it can be removed without harmful solvents. The energy demand has been reduced by optimizing pressure and temperature conditions to lower operational costs while maintaining high extraction efficiencies.[19] The environmental advantages and high oil quality make SFE a distinctive technology used in the biofuel industry.[19]

Ultrasonic-Assisted Extraction (UAE)

UAE uses ultrasonic waves to disrupt algal cell walls, which release lipids without requiring extensive pretreatment.[20] Ultrasonic waves create mechanical vibrations, which eventually result in efficient rupture of cell walls through the formation of microjets and cavitation bubbles.[20] This technique operates at room temperature, thus significantly reducing thermal footprints and energy requirements. Research underway seeks ways to scale up this technology for industrial applications by determining optimal frequencies and intensities for different algae species.[20]

Enzymatic Extraction

Applying specific enzymes to break down algae membranes or cell walls presents an environmentally friendly alternative for extracting oil.[21] Such enzymatic hydrolysis destroys cell polysaccharides and proteins, leading to the selective liberation of lipid droplets.[21] It is characterized by mild operating conditions, which lowers energy consumption and preserves the quality characteristics of final products, resulting in enhanced economic viability and broader applicability on larger scales. Biotechnological advances are being made toward developing more effective and cheaper enzymes, making this method more feasible for large-scale implementation.[21]

Microwave-Assisted Extraction (MAE)

By heating algal biomass with microwave energy, MAE causes rapid pressure build-up within the cells, leading to their rupture.[22] This approach combines thermal and non-thermal effects to improve lipid extraction rates. MAE has low solvent consumption and short processing time compared to other methods, making it a green technology.[22] Enhancing the sustainability of the process entails researching the optimization of microwave irradiation parameters and investigating solvent-free protocols.[22]

Solvent-Based Extraction Optimization

Traditional solvent extraction techniques, although widely used, are currently being improved to increase efficiency while reducing their impact on the environment.[23] Some improvements include the selection of greener solvents with less toxicity and the introduction of continuous extraction systems that require a minimum amount of solvents.[23] Ethyl acetate is widely used for its low toxicity and relatively easy recovery. Moreover, waste reduction and operation cost-cutting can be achieved by integrating solvent recovery and recycling strategies.[23]

Integrated Biorefinery Approaches

Integrating oil extraction into biorefinery contexts allows for maximizing the realization of value from various components found in algal biomass.[24] Besides lipids for biofuel production, this approach also seeks to obtain proteins, carbohydrates, or pigments with applications in food industries, feed industries, or industries in general.[24] The biorefinery concept maximizes economic viability in microalgae cultivation, thus addressing one of the significant concerns regarding the cost-effectiveness of biofuel production compared with traditional fuels.[24]

Conclusion

Technological advances in this review have been examined regarding algae-based biofuel production. Their cultivation, harvesting, lipid accumulation, and oil extraction have been identified as some of the strategies that are overcoming age-old barriers. Technological advances range from hybrid systems and waste utilization for cultivation to electro-coagulation-flocculation and foam flotation for harvesting, making production more efficient and sustainable. Moreover, oil extraction through supercritical CO2 extraction and other emerging technologies guarantees environmental friendliness. These advancements push the frontiers of biofuel technology towards a future of renewable energy, which is consistent with environmental imperatives and sustainability.

To achieve global carbon neutrality goals, moving away from fossil fuels towards renewable energy sources as soon as possible is necessary. Therefore, we must concentrate our efforts on those branches of algal biofuel technology that seem most likely to succeed. One area that needs more research is hybrid systems for cultivation, which combine the benefits of open ponds with photobioreactors. Photobioreactors can control environmental conditions while open ponds are cheap; this equipment has the potential to maximize both biomass productivity and quality.

In terms of harvesting technology, electro-coagulation-flocculation needs development and optimization, most notably because this method stands out as an environmentally friendly process that saves energy besides being cost-effective when compared to traditional processes, which use more chemicals, thereby becoming greener, too. Therefore, we should refine electro- coagulation-flocculation's efficiency to support large-scale sustainable production systems for algal biodiesel.

Further work should be done in these areas while considering economic aspects if we are going to tap fully into the potentiality of algae as feedstocks for alternative fuels. Continuous innovation coupled with supportive policy will enable us to meet global demands for cleaner energy sources, making biodegradable automotive fuel produced from microalgae a viable option economically.

Acknowledgments

I would like to acknowledge Sarah Olshan and Forest Malley from Lumiere and Amy VanHoesen from Pomfret School for their support.

References

(1) Elzen, M. D.; Fekete, H.; Höhne, N.; Admiraal, A.; Forsell, N.; Hof, A. F.; Olivier, J. G. J.; Roelfsema, M.; Van Soest, H. Greenhouse Gas Emissions from Current and Enhanced Policies of China until 2030: Can Emissions Peak before 2030? *Energy Policy* **2016**, *89*, 224–236. https://doi.org/10.1016/j.enpol.2015.11.030.

(2) Saad, M. G.; Dosoky, N. S.; Zoromba, M. S.; Shafik, H. M. Algal Biofuels: Current Status and Key Challenges. *Energies* **2019**, *12* (10), 1920. https://doi.org/10.3390/en12101920.

(3) Zhang, S.; Zhang, L.; Li, X. A Review on Biodiesel Production from Microalgae: Influencing Parameters and

Recent Advanced Technologies. *Front. Microbiol.* **2022**, *13*. https://doi.org/10.3389/fmicb.2022.970028.

(4) Saad, M. G.; Dosoky, N. S.; Zoromba, M. S.; Shafik, H. M. Algal Biofuels: Current Status and Key Challenges. *Energies* **2019**, *12* (10), 1920. https://doi.org/10.3390/en12101920.

(5) Narala, R. R.; Garg, S.; Sharma, K. K.; Thomas-Hall, S. R.; Deme, M.; Li, Y.; Schenk, P. M. Comparison of Microalgae Cultivation in Photobioreactor, Open Raceway Pond, and a Two-Stage Hybrid System. *Front. Energy Res.* **2016**, *4*. https://doi.org/10.3389/fenrg.2016.00029.

(6) Kröger, M.; Müller-Langer, F. Review on Possible Algal-Biofuel Production Processes. *Biofuels* **2012**, *3* (3), 333–349. https://doi.org/10.4155/bfs.12.14.

(7) González-López, C. V.; Acién Fernández, F. G.; Fernández-Sevilla, J. M.; Sánchez Fernández, J. F.; Molina Grima, E. Development of a Process for Efficient Use of CO_2 from Flue Gases in the Production of Photosynthetic Microorganisms. *Biotechnol. Bioeng.* **2012**, *109* (7), 1637–1650. https://doi.org/10.1002/bit.24446.

(8) Menegazzo, M. L.; Fonseca, G. G. Biomass Recovery and Lipid Extraction Processes for Microalgae Biofuels Production: A Review. *Renew. Sustain. Energy Rev.* **2019**, *107*, 87–107. https://doi.org/10.1016/j.rser.2019.01.064.

(9) Gao, F.; Yang, H.-L.; Li, C.; Peng, Y.-Y.; Lu, M.-M.; Jin, W.-H.; Bao, J.-J.; Guo, Y.-M. Effect of Organic Carbon to Nitrogen Ratio in Wastewater on Growth, Nutrient Uptake and Lipid Accumulation of a Mixotrophic Microalgae Chlorella Sp. *Bioresour. Technol.* **2019**, *282*, 118–124. https://doi.org/10.1016/j.biortech.2019.03.011.

(10) Wu, Q.; Guo, L.; Li, X.; Wang, Y. Effect of Phosphorus Concentration and Light/Dark Condition on Phosphorus Uptake and Distribution with Microalgae. *Bioresour. Technol.* **2021**, *340*, 125745. https://doi.org/10.1016/j.biortech.2021.125745.

(11) Yang, Z.-Y.; Gao, F.; Liu, J.-Z.; Yang, J.-S.; Liu, M.; Ge, Y.-M.; Chen, D.-Z.; Chen, J.-M. Improving Sedimentation and Lipid Production of Microalgae in the Photobioreactor Using Saline Wastewater. *Bioresour. Technol.* **2022**, *347*, 126392. https://doi.org/10.1016/j.biortech.2021.126392.

(12) Yan, C.; Zhu, L.; Wang, Y. Photosynthetic CO2 Uptake by Microalgae for Biogas Upgrading and Simultaneously Biogas Slurry Decontamination by Using of Microalgae Photobioreactor under Various Light Wavelengths, Light Intensities, and Photoperiods. *Appl. Energy* **2016**, *178*, 9–18. https://doi.org/10.1016/j.apenergy.2016.06.012.

(13) Xin, L.; Hong-ying, H.; Yu-ping, Z. Growth and Lipid Accumulation Properties of a Freshwater Microalga Scenedesmus Sp. under Different Cultivation Temperature. *Bioresour. Technol.* **2011**, *102* (3), 3098–3102. https://doi.org/10.1016/j.biortech.2010.10.055.

(14) Herrero, M.; Mendiola, J. A.; Cifuentes, A.; Ibáñez, E. Supercritical Fluid Extraction: Recent Advances and Applications. *J. Chromatogr. A* **2010**, *1217* (16), 2495–2511. https://doi.org/10.1016/j.chroma.2009.12.019.

(15) Tazikeh, S.; Zendehboudi, S.; Ghafoori, S.; Lohi, A.; Mahinpey, N. Algal Bioenergy Production and

Utilization: Technologies, Challenges, and Prospects. *J. Environ. Chem. Eng.* **2022**, *10* (3), 107863. https://doi.org/10.1016/j.jece.2022.107863.

(16) Hoang, A. T.; Sirohi, R.; Pandey, A.; Nižetić, S.; Lam, S. S.; Chen, W.-H.; Luque, R.; Thomas, S.; Arıcı, M.; Pham, V. V. Biofuel Production from Microalgae: Challenges and Chances. *Phytochem. Rev.* **2023**, *22* (4), 1089–1126. https://doi.org/10.1007/s11101-022-09819-y.

(17) Ambaye, T. G.; Vaccari, M.; Bonilla-Petriciolet, A.; Prasad, S.; Van Hullebusch, E. D.; Rtimi, S. Emerging Technologies for Biofuel Production: A Critical Review on Recent Progress, Challenges and Perspectives. *J. Environ. Manage.* **2021**, *290*, 112627. https://doi.org/10.1016/j.jenvman.2021.112627.

(18) Griffiths, G.; Hossain, A. K.; Sharma, V.; Duraisamy, G. Key Targets for Improving Algal Biofuel Production. *Clean Technol.* **2021**, *3* (4), 711–742. https://doi.org/10.3390/cleantechnol3040043.

(19) Uwineza, P. A.; Waśkiewicz, A. Recent Advances in Supercritical Fluid Extraction of Natural Bioactive Compounds from Natural Plant Materials. *Molecules* **2020**, *25* (17), 3847. https://doi.org/10.3390/molecules25173847.

(20) Kumar, K.; Srivastav, S.; Sharanagat, V. S. Ultrasound Assisted Extraction (UAE) of Bioactive Compounds from Fruit and Vegetable Processing by-Products: A Review. *Ultrason. Sonochem.* **2021**, *70*, 105325. https://doi.org/10.1016/j.ultsonch.2020.105325.

(21) Streimikyte, P.; Viskelis, P.; Viskelis, J. Enzymes-Assisted Extraction of Plants for Sustainable and Functional Applications. *Int. J. Mol. Sci.* **2022**, *23* (4), 2359. https://doi.org/10.3390/ijms23042359.

(22) Cerdá-Bernad, D.; Baixinho, J. P.; Fernández, N.; Frutos, M. J. Evaluation of Microwave-Assisted Extraction as a Potential Green Technology for the Isolation of Bioactive Compounds from Saffron (Crocus Sativus L.) Floral By-Products. *Foods* **2022**, *11* (15), 2335. https://doi.org/10.3390/foods11152335.

(23) Seo, C.-S.; Kim, J.-H.; Shin, H.-K. Optimization of the Extraction Process for the Seven Bioactive Compounds in Yukmijihwang-Tang, an Herbal Formula, Using Response Surface Methodology. *Pharmacogn. Mag.* **2014**, *10* (39), 606. https://doi.org/10.4103/0973-1296.139798.

(24) Qiao, J.; Cui, H.; Wang, M.; Fu, X.; Wang, X.; Li, X.; Huang, H. Integrated Biorefinery Approaches for the Industrialization of Cellulosic Ethanol Fuel. *Bioresour. Technol.* **2022**, *360*, 127516. https://doi.org/10.1016/j.biortech.2022.127516.