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Research Article

Algal Biofuels and Bioproducts: research trends and prospects

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ABSTRACT:

Microalgae and macro-algae are recognised as strategic third-generation feedstocks for both liquid and gaseous biofuels, alongside high-value bioproducts like nutraceuticals and biofertilizers. The objective of this review is to evaluate the current technological landscape of algal biotechnology, examining diverse cultivation systems, conversion pathways, and the shift toward integrated biorefinery models. While algae offer significant environmental benefits—including high CO_2 fixation and non-competition with arable land—large-scale production remains pre-commercial due to prohibitive costs in cultivation, harvesting, and downstream processing. This paper highlights critical research gaps, such as the need for low-energy dewatering methods, robust strain engineering via synthetic biology, and the optimisation of wastewater-integrated systems. As the industry moves from a fuel-only focus toward diversified biorefineries, achieving cost-competitive and carbon-efficient algal biofuels at scale is still the central challenge for the coming decade.

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1. Introduction

In recent times, there has been an increasing demand for alternative and sustainable energy resources, attributed to the rapid climate changes, depletion of non-renewable resources, air pollution, air-pollution and other serious environmental factors. As a result, one of the most promising alternative and sustainable energy resources of bioenergy is algal biofuels and bioproducts. Biomass like micro algae and macro algae offers great productivity, excellent growth and capacity to use non-arable land, concentrated carbon dioxide, wastewater or saline water for making a third-generation biofuel feedstock.

Several factors, like climate change, depletion of non-renewable energy resources, air pollution, et cetera, have increased the demand for alternative and sustainable fuel. A bio like micro algae and macro algae are the promising Bhai resources which offer high productivity, rapid growth rate and ability to utilise the non-arable land. (Anto et al., 2020; Ganesan et al., 2020; Sarwer et al., 2022; Kumar et al., 2020; Chen et al., 2019; Saad et al., 2019; Jabłońska-Trypuć et al., 2023).

The fact that algae can be converted into thermochemical fuels, biogas, bio, hydrogen, biodiesel, and bioethanol along with the ability to supply pigments, fertilisers, polyunsaturated, fatty acids, polysaccharides, and other byproducts, make algae one of the most popular and easy to use sources of bio production(Ganesan et al., 2020; Wang et al., 2023; Sarwer et al., 2022; Kumar et al., 2020; Chen et al., 2019). Constraints like high energy production cost, energy-intensive harvesting and drying and underdeveloped large-scale infrastructure are some limitations that restrict the limited market access of algal biofuels and bio products (Khoo et al., 2023; Anto et al., 2020; Ganesan et al., 2020; Sarwer et al., 2022; Kumar et al., 2020; Chen et al., 2019; Saad et al., 2019; Jabłońska-Trypuć et al., 2023). During recent times, the research works focus more on integrating algal biorefineries, metabolic and genetic engineering and circular bioeconomic concepts to develop both sustainability and economics. (Khoo et al., 2023; Wang et al., 2023; Sarwer et al., 2022; Kumar et al., 2020; Chen et al., 2019; Jabłońska-Trypuć et al., 2023)

2. Algal Feedstocks and Bioproduct Potential

2.1 Microalgae and macroalgae

Micro algae provide carbohydrate which biogas without requiring freshwater or fertilisers. Also, these microalgae possess high carbohydrate and lipid content and show much higher productivity than terrestrial crops (Ganesan et al., 2020; Wang et al., 2023; Sarwer et al., 2022; Kumar et al., 2020; Chen et al., 2019). A wide area of microalgae, such as those that are widely studied and explored for biogas and biofuels production. On the contrary, red seaweeds like *Chlorella, Nannochloropsis, and Scenedesmus* and brown algae are particularly useful for fermentation, biochemicals and bioethanol (Ganesan et al., 2020; Wang et al., 2023; Sarwer et al., 2022; Kumar et al., 2020).

2.2 Biofuels

Algal biomass can be transformed into multiple fuel types **(Table1)**

Biofuel	Substrate	Conversion Process	Remarks	References
Biodiesel	Triacylglycerols (lipid fraction of micro/macroalgae)	Transesterification	Most researched route; compatible with existing diesel engines	Khoo et al., 2023; Anto et al., 2020; Ganesan et al., 2020; Sarwer et al., 2022; Kumar et al., 2020; Chen et al., 2019; Saad et al., 2019; Jabłońska-Trypuć et al., 2023
Bioethanol (and other alcohols)	Fermentable carbohydrates in micro- or macroalgal biomass	Pretreatment → Saccharification → Fermentation	Requires breakdown of complex carbohydrates into fermentable sugars	Ganesan et al., 2020; Sarwer et al., 2022; Kumar et al., 2020
Biogas	Whole biomass or residual biomass after lipid extraction	Anaerobic digestion	Utilises residual biomass, enhancing overall process efficiency	Ganesan et al., 2020; Sarwer et al., 2022; Kumar et al., 2020; Bhushan et al., 2020
Biohydrogen	Whole or residual biomass	Dark fermentation	Biological hydrogen production under anaerobic conditions	Ganesan et al., 2020; Sarwer et al., 2022; Kumar et al., 2020; Bhushan et al., 2020
Syngas	Whole biomass	Gasification	Produces a mixture of CO and H_2 for energy or chemical synthesis	Ganesan et al., 2020; Sarwer et al., 2022; Kumar et al., 2020; Maliha & Abu-Hijleh, 2022
Bio-oil & Biochar	Whole biomass	Pyrolysis / Hydrothermal liquefaction	Thermochemical conversion yielding liquid and solid biofuels	Ganesan et al., 2020; Sarwer et al., 2022; Kumar et al., 2020; Maliha & Abu-Hijleh, 2022; Bhushan e

Table 1. Transformed products from algal biomass.

2.3 High-value bioproducts

The diverse array of high-value compounds produced by micro algae and macro algae, such as carotenoids, phycobiliproteins, fatty acids, structural and storage polysaccharides, polyunsaturated fatty acids, bio fertilisers, and bio stimulants, has significantly increased the economic feasibility of algae cultivation systems (Wang et al., 2023; Sarwer et al., 2022; Kumar et al., (2020; Chen et al., 2019). The ability of algae to produce Biofuels alongside these value-added products have resulted in the principle of integrated algal biorefinery (Wang et al., 2023; Sarwer et al., 2022; Kumar et al., 2020; Chen et al., 2019) Table 2.

3. Industrial Algal Production Systems

3.1 Cultivation methods and systems

Algae are cultivated under autotrophic, heterotrophic, or mixotrophic conditions using:

Table 2: Cultivation system

Cultivation System	Advantages	Mummy Disadvantages	Best Suited For	References
Open Raceway Ponds	Low capital cost	Vulnerable to contamination, evaporation losses, variable productivity	Large-scale, low-cost production	Anto et al., 2020; Ganesan et al., 2020; Kumar et al., 2020; Chen et al., 2019; Saad et al., 2019; Jabłońska-Trypuć et al., 2023
Closed PBRs	High control over contamination, light, and CO_2; improved productivity	Much higher capital and operating costs	Controlled, high-productivity growth	Anto et al., 2020; Ganesan et al., 2020; Kumar et al., 2020; Chen et al., 2019; Saad et al., 2019; Jabłońska-Trypuć et al., 2023
Hybrid Systems	Balances cost and control (PBR inoculum + open ponds)	N/A (proposed optimisation)	Scalable production with reliability	Anto et al., 2020; Ganesan et al., 2020; Saad et al., 2019

The composition of yield is greatly impacted by key operational parameters like mixing, light, intensity, carbon dioxide, and nutrient supply (Anto et al., 2020; Ganesan et al., 2020; Kumar et al., 2020; Chen et al., 2019; Saad et al., 2019; Jabłońska-Trypuć et al., 2023).

3.2 Wastewater and biomass production integration

Simultaneous wastewater treatment and biomass production offers nutrient recycling, cost reduction, and environmental co-benefits. Municipal, agricultural and industrial wastewater serve as the source of nutrients and also help in mitigating problems related to effluent loads (Ganesan et al., 2020; Sarwer et al., 2022; Kumar et al., 2020). The carbon sequestration capacity of microalgae is approximately 1.3 KG carbon dioxide per kg biomass (Sarwer et al., 2022).

3.3 Harvesting and dewatering

For harvesting, the preferred methodologies are flocculation, sedimentation, filtration, or centrifugation, but they are very costly, particularly at low concentrations, typical of open ponds (Anto et al., 2020; Ganesan et al., 2020; Kumar et al., 2020; Chen et al., 2019; Bhushan et al., 2020; Saad et al., 2019; Jabłońska-Trypuć et al., 2023). Promising results have been obtained by the use of biological flocculation and magnetic or nano particle assisted techniques, which have shown great results in hard-to-treat which sometimes reaching 80 to 90%. However, the environmental and economic impacts of these nanomaterials demand further evaluation (Bhushan et al., 2020)

4. Pretreatment and Conversion Pathways

4.1 Cell disruption method. Table 3

Method Category	Examples	Benefits	Drawbacks	Applications	References
Physical	Bead milling, ultrasonication	Improves access to intracellular lipids/carbohydrates	High energy consumption	General cell wall disruption	Anto et al., 2020; Ganesan et al., 2020; Kumar et al., 2020; Bhushan et al., 2023; Chen et al., 2019; Saad et al., 2019; Jabłońska-Trypuć et al., 2023
Chemical	Acid/alkali treatment	Effective cell wall breakdown	Chemical usage, potential residue	Biomass liquefaction	Anto et al., 2020; Ganesan et al., 2020; Kumar et al., 2020; Bhushan et al., 2023; Chen et al., 2019; Saad et al., 2019; Jabłońska-Trypuć et al., 2023
Biological	Enzymatic, microbial (whole-cell, fungal, bacterial)	Lower energy, selective fractionation	Slower process, specificity needed	Biogas, biohydrogen, ethanol production (recently highlighted as promising)	Anto et al., 2020; Ganesan et al., 2020; Kumar et al., 2020; Bhushan et al., 2023; Bhushan et al., 2020; Chen et al., 2019; Saad et al., 2019; Jabłońska-Trypuć et al., 2023
Advanced (Hydrothermal/Microwave)	Hydrothermal, microwave-assisted	Disrupts walls + liquefies biomass simultaneously	High energy inputs, chemical usage	Rapid processing	Anto et al., 2020; Ganesan et al., 2020; Bhushan et al., 2023; Chen et al., 2019; Jabłońska-Trypuć et al., 2023

Table3: Cell disruption techniques

4.2 Lipid extraction and biodiesel

Lipid recovery utilises solvent-based extraction (hexane, chloroform-methanol), supercritical CO_2, and green. solvents. While transesterification is technologically mature, achieving cost-effective, high-purity lipids at scale remains difficult due to intensive drying and solvent recovery requirements. (Khoo et al., 2023; Anto et al., 2020; Ganesan et al., 2020; Sarwer et al., 2022; Kumar et al., 2020; Chen et al., 2019; Jabłońska-Trypuć et al., 2023).

4.3 Fermentation to bioethanol and other fuels

Pretreatment and saccharification of carbohydrate-rich algae release sugars for bioethanol or butanol fermentation. However, incomplete hydrolysis, inhibitor formation, and the need for robust, multi-sugar-utilising microbes remain significant challenges. (Ganesan et al., 2020; Sarwer et al., 2022; Kumar et al., 2020).

4.4 Thermochemical routes and anaerobic digestion

Pyrolysis, gasification, and hydrothermal liquefaction (HTL) convert algae into bio-oil and syngas. Anaerobic digestion generates biogas but requires pretreatment or co-digestion to manage ammonia inhibition and recalcitrant cell walls (Ganesan et al., 2020; Sarwer et al., 2022; Kumar et al., 2020; Bhushan et al., 2023; Bhushan et al., 2020).

5. Strain, improvement and enzyme technologies.

5.1 Strain improvement and metabolic engineering

Using the latest techniques like metabolic engineering and genetic modifications, it has been possible to increase the lipid accumulation, enhance stress tolerance, and redirect the carbon flux (Khoo et al., 2023; Sarwer et al., 2022; Chen et al., 2019; Jabłońska-Trypuć et al., 2023). Various approaches, like modulation of light, harvesting, antenna size, knockdown of enzymes in biosynthesis of lipid metabolism and introduction of heterologous pathways for novel products, have been adopted. For the generation of improved strains, techniques like adaptive evolution and mutagenesis are used, paving the way for algal "cell factories" for targeted production of bio- products (Khoo et al., 2023; Sarwer et al., 2022; Chen et al., 2019; Jabłońska-Trypuć et al., 2023).

Although there has been a great advancement in this field of algal biotechnology, there are serious issues related to biosafety, public acceptance, and regulatory constraints on genetically modified algal products (Sarwer et al., 2022; Chen et al., 2019; Jabłońska-Trypuć et al., 2023)

5.2 Enzyme and microbial engineering for pretreatment and conversion

For enhancing the saccharification process and biogas yield, scientists are using various biological pretreatment like genetically engineered enzymes and microbial consortia. These genetically modified enzymes, like cellulases, hemicellulases, and accessory enzymes, are efficiently improving the production yield (Bhushan et al., 2023; Bhushan et al., 2020).

6. Algal Biorefineries and Circular Bioeconomy

6.1 Biorefinery concepts

The concept of algal biorefinery is quite interesting, and it amalgamates the conversion pathways to co-produce fertilisers, chemicals, fuels, and other materials, thereby developing profitability and resource efficiency (Wang et al., 2023; Sarwer et al., 2022; Kumar et al., 2020; Chen et al., 2019). During recent times, the conceptual designs, so far adopted by the scientist's lipid centric biodiesel platforms involving anaerobic digestions of residues to carbohydrate-focused macro bio refineries, generating ethanol and feed products (Wang et al., 2023; Sarwer et al., 2022; Kumar et al., 2020; Chen et al., 2019)

6.2 Role in circular bioeconomy and environmental services

Macro and micro algae are not only useful for biofuel generation, but it also creates multiple ecosystem services like nutrient recycling, carbon sequestration, soil enhancement through algae-derived bio fertilizers and wastewater treatments. On monetization of these services through carbon credits or nutrient trading schemes, one could improve the economics of algal platforms. (Sarwer et al., 2022)

7. Techno-Economic and Environmental Assessments

Techno-economic and life cycle assessments (TEA/LCA) identify cultivation (~77% of cost), harvesting, and drying as the primary energy and economic hotspots. Algal biofuels currently struggle to compete with fossil fuels due to high electricity and infrastructure requirements. While they offer significant emission reduction potential, their long-term viability depends on integrating co-products, utilising low-cost inputs, and system-level optimisation (Ganesan et al., 2020; Wang et al., 2023; Sarwer et al., 2022; Jabłońska-Trypuć et al., 2023)

8. Research Gaps

The research focuses on transitioning algal biorefineries from laboratory concepts to commercial-scale realities by addressing critical bottlenecks in low-cost cultivation, multi-product integration, and industrial strain translation (Anto et al., 2020; Sarwer et al., 2022). By employing standardised systems-level optimisation and Techno-Economic Analysis (TEA), the work aims to create a sustainable circular economy model that couples biofuel production with environmental services like wastewater treatment and CO_2 sequestration (Wang et al., 2023; Kumar et al., 2020; Jabłońska-Trypuć et al., 2023)

9. CONCLUSION

Transitioning from single-product biodiesel toward more realistic, integrated biorefinery and circular bioeconomy models is the future of algal biotechnology. Micro- and macroalgal systems can deliver low-carbon fuels, high-value products, and environmental services, but widespread application depends on breakthroughs in large-scale cultivation, low-energy harvesting and conversion, industrial strain engineering, and enabling policy and market frameworks. By extracting high-value co-products such as pigments, nutraceuticals, and proteins alongside biofuels, the economic challenges of production can be mitigated. No doubt, the commercial viability of these technologies will depend on supportive policies such as carbon credits and R&D subsidies, which will bridge the gap between pilot-scale success and global industrial adoption.

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