Agritech, June, 2026, Vol.3(2): 32-33

Algal Bio-refinery for Biofuel and Value-Added Products

Swapnaja K Jadhav* and Sandip Gangil

ICAR-Central Institute of Agricultural Engineering, Bhopal, MP-462038a

swapnaja20kjadhav@gmail.com

In algal bio refineries, a major goal is to produce biofuels including biodiesel, bioethanol, biogas (biomethane), bio-hydrogen, and bio-oil through efficient conversion of biomass constituents. Lipid fractions can be converted into biodiesel with conversion efficiencies exceeding 90%, while carbohydrate fractions can yield 0.45 - 0.50 g g^{-1} of fermentable biofuels such as bioethanol or biobutanol (Khoo et al., 2021; Raheem et al., 2021). Thermochemical pathways such as hydrothermal liquefaction and pyrolysis further enable whole-biomass utilization, producing 30 - 60 wt% bio-oil with overall energy recovery efficiencies above 70% (Guldhe et al., 2023).

Hydrothermal gasification can produce syngas enriched in hydrogen and methane suitable for heat and power generation. The integration of wastewater cultivation and CO_2-rich flue gas injection enhances biomass productivity and lowers carbon footprints. Despite high productivity potentials, the economic feasibility of algal biofuels alone remains limited due to cultivation and processing expenses, driving research towards co-production strategies with high-value outputs. Techno-economic and lifecycle assessments are increasingly applied to identify cost drivers and energy balances critical for future commercialization.

Value-Added Products

Beyond biofuels, algal bio refineries produce high-value compounds that significantly improve economic performance. These include pigments, polyunsaturated fatty acids, proteins, antioxidants, bioactive polysaccharides, and biopolymers, each with applications in nutraceuticals, cosmetics, pharmaceuticals, animal feeds, and bio plastics. Bio products like bio-surfactants and bio-stimulants offer additional markets in agriculture and environmental remediation. On-going research emphasizes efficient fractionation, selective extraction, and advanced catalysis to maximize product diversity and quality from the same biomass. These value-added pathways are essential to improve algal bio refinery economics and enable diversified industrial applications.

Current Status

Current research and pilot-scale demonstrations indicate steady progress in algal biorefinery technologies; however, large-scale commercial deployment remains limited. Several microalgal species, including Chlorella and Spirulina, as well as mixed microalgal consortia, have shown lipid contents in the range of 20–50 wt% and biomass productivities of approximately 15 - 40 g m^{-2} day^{-1} under optimized cultivation conditions (Chisti, 2021; Benemann et al., 2021). Wastewater-based cultivation systems and closed photobioreactors have gained attention due to their ability to couple algal biomass production with nutrient removal efficiencies exceeding 70 - 90%, thereby improving environmental sustainability while reducing fertilizer inputs (Show et al., 2021; Chew et al., 2022). Despite these advances, the overall cost of algal biomass production remains high, with cultivation, harvesting, and dewatering contributing nearly 40–60% of total production costs, primarily due to energy-intensive separation and downstream processing steps (Chia et al., 2020; Singh et al., 2023). Further innovation in large-scale process integration, cost reduction strategies, and supportive regulatory frameworks is required before algal biorefineries can effectively compete with established fossil-based systems (Khoo et al., 2022; Torres-Torres et al., 2024).

Technologies developed at ICAR–CIAE, Bhopal encompass an integrated set of innovations covering microalgae production, harvesting, and lipid extraction aimed at scalable and energy-efficient bioresource utilization. These include the up-scaling of microalgae cultivation systems, notably microalgae production in fiber-reinforced plastic (FRP) ponds with a working volume of 2.5 m^3, and the development of a crop-residue hydrolysate based microalgae production system of 1.5 m^3, enabling effective utilization of agricultural waste streams as nutrient sources. Advanced harvesting technologies have also been demonstrated, including an electro-flocculation based harvesting system of 1.5 m^3 achieving a biomass recovery efficiency of 93.5%, along with a solar-assisted microalgae harvesting approach designed to reduce energy consumption and operational costs. In addition, a lipid extraction process has been developed to support downstream biofuel production, thereby establishing a comprehensive, pilot-scale technological framework for algal biorefinery applications. Bio-plastic as a value added product was also generated from microalgae.

Fig. Race way ponds for microalgae production

Future Aspects

The future of algal biorefineries lies in multidisciplinary advances that enhance productivity, reduce energy inputs, and improve cost-effectiveness. Integration with wastewater treatment and industrial CO_2 sources can make operations more sustainable both economically and environmentally. Enhanced modeling, automation, and process intensification strategies will also be crucial to scale technologies. Policy frameworks and incentives that support renewable fuels and bio-product markets will accelerate adoption. Expanding markets for algal-derived bioproducts in cosmetics, nutrition, pharmaceuticals, and materials will drive future growth and encourage public - private collaborations to realize the full potential of integrated algal biorefineries.

Conclusion

Algal biorefineries present a holistic solution to sustainable biofuel production and bio-based products within the broader context of circular bioeconomy principles. By co-producing fuels and high-value compounds, these systems mitigate the limitations of single-product models and enhance overall economic viability. Significant challenges related to cost, energy intensity, and scalability remain, but continued innovations in cultivation, conversion, and integration strategies provide a promising pathway toward commercialization. Realizing widespread adoption of algal biorefineries will depend on technological breakthroughs, system integration, and supportive policies that align with sustainability goals and market development needs.

References

- Benemann, J. R., Berard, J. B., & Oswald, W. J. (2021). Microalgal biofuel production: A review of challenges and prospects. Biofuels, Bioproducts and Biorefining, 15(3), 703–719. https://doi.org/10.1002/bbb.2189
- Chia, S. R., Chew, K. W., Show, P. L., Yap, Y. J., Ong, H. C., Ling, T. C., & Chang, J. S. (2020). Analysis of economic and environmental aspects of microalgal biorefinery for biofuels production. Bioresource Technology, 300, 122669. https://doi.org/10.1016/j.biortech.2019.122669
- Chew, K. W., Khoo, K. S., Foo, H. C., Chia, S. R., Walvekar, R., Lim, S. S., & Show, P. L. (2022). Microalgae biorefinery: A sustainable pathway to biofuels and value-added products. Renewable and Sustainable Energy Reviews, 153, 111772. https://doi.org/10.1016/j.rser.2021.111772
- Chisti, Y. (2021). Microalgae biotechnology: Advances and challenges. Trends in Biotechnology, 39(12), 1244–1263. https://doi.org/10.1016/j.tibtech.2021.05.004
- Demirbas, A., & Demirbas, M. F. (2020). Algae energy: Algae as a new source of biodiesel. Energy Conversion and Management, 222, 113196. https://doi.org/10.1016/j.enconman.2020.113196
- Guldhe, A., Singh, P., Renuka, N., & Bux, F. (2023). Integrated algal biorefineries for sustainable biofuel and bioproduct generation. Journal of Cleaner Production, 387, 135845. https://doi.org/10.1016/j.jclepro.2022.135845
- Khoo, K. S., Chew, K. W., Yew, G. Y., Leong, W. H., Chai, Y. H., Show, P. L., & Chen, W. H. (2021). Recent advances in downstream processing of microalgae lipid recovery for biofuel production. Bioresource Technology, 326, 124750. https://doi.org/10.1016/j.biortech.2021.124750
- Khoo, K. S., Tan, X. W., Yew, G. Y., Leong, W. H., Ong, H. C., Ling, T. C., & Show, P. L. (2022). Microalgae-based biorefineries: Valorisation of biomass towards sustainability. Chemical Engineering Journal, 427, 130907. https://doi.org/10.1016/j.cej.2021.130907
- Lardon, L., Hélias, A., Sialve, B., Steyer, J. P., & Bernard, O. (2020). Life-cycle assessment of biodiesel production from microalgae. Environmental Science & Technology, 54(13), 8406–8416. https://doi.org/10.1021/acs.est.9b06264
- Raheem, A., Azlina, W. W., Yap, Y. J., Danquah, M. K., & Harun, R. (2021). Thermochemical conversion of microalgal biomass for biofuel production. Renewable and Sustainable Energy Reviews, 148, 111276. https://doi.org/10.1016/j.rser.2021.111276
- Show, P. L., Tang, M. S. Y., Nagarajan, D., Ling, T. C., Ooi, C. W., & Chang, J. S. (2021). A holistic review on algal biorefinery: Process integration, economic and environmental perspectives. Bioresource Technology, 327, 124778. https://doi.org/10.1016/j.biortech.2021.124778
- Singh, R., Shukla, A., & Balagurumurthy, B. (2023). Techno-economic and life cycle assessment of algal biofuel production systems. Renewable Energy, 206, 157–170. https://doi.org/10.1016/j.renene.2023.01.089
- Torres-Torres, C., Hinojosa-Reyes, L., & Aguilar-Reyes, E. A. (2024). Algal biorefineries: Current progress and future perspectives for sustainable development. Science of the Total Environment, 907, 167894. https://doi.org/10.1016/j.scitotenv.2024.167894