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Algal Biorefineries: Emerging Platforms for Circular Bioeconomy and Sustainable Bioproduct Generation

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ABSTRACT: Growing concerns regarding fossil fuel depletion, greenhouse gas emissions, and environmental sustainability have accelerated the development of renewable biomass-based technologies. Among these, algal biorefineries represent an innovative and sustainable platform to transform algal biomass into various services of high added value products in a circular bioeconomy context. In contrast to traditional petroleum refineries, algal biorefineries employ microalgae and macroalgae as sustainable feedstocks for the simultaneous production of biofuels, biochemicals, biomaterials and bioenergy. This review gives an overview of the recent progress in algal biorefinery systems focused on biomass cultivation, harvesting, fractionation, and conversion technologies.

It also elaborates on major algal biorefinery approaches, covering the feedstock used and bio-based products derived from microalgal, macroalgal, integrated whole-biomass algal, and wastewater-based systems. Include important conversion pathways (e.g., transesterification, fermentation, anaerobic digestion and thermochemical processing) for the production of biodiesel bioethanol biogas and renewable chemicals. Not only is utilized for bioenergy production, algae are essential sources of other high-value compounds such as proteins, pigments, antioxidants and polyunsaturated fatty acids which are useful in food (as alimentary supplements), pharmaceutical or nutraceutical industries. Several issues remain with regards to the efficiency of cultivation, harvesting and processing techniques as well as commercial viability, despite technological advancements. Algal biorefineries present important opportunities for sustainable biomass valorisation, and are a critical component of future low carbon circular bioeconomy pathways.

1. INTRODUCTION

Driven by the rapid depletion of fossil fuel reserves, rising greenhouse gas (GHG) emissions and increasing environmental sustainability concerns, global society is on a historic transition from traditional linear production systems toward renewable and circular production systems. Biorefineries are one of the most prominent future sustainable technologies, which can directly convert renewable biomass to many value-added products from biomass in an integrated manner with minimum environmental impact. In the context of circular bioeconomy, biorefineries can be considered a paradigm change that enable efficient resource use, waste valorization, carbon reduction and advancing sustainable industrial development (Kamm & Kamm, 2004; Cherubini, 2010; de Jong & Jungmeier, 2015).

The concept of biorefinery is analogous to conventional petroleum refineries; however, instead of processing fossil-based feedstocks, biorefineries utilize renewable biological resources such as agricultural residues, forestry biomass, industrial by-products, municipal organic waste, and aquatic biomass to generate biofuels, biochemicals, biomaterials, and bioenergy. In

contrast, biorefineries use one or more integrated biological, chemical, thermochemical and/or biochemical conversion pathways to maximize the utilization of biomass while minimizing waste generation and maximizing sustainability of overall process (Cherubini 2010). With the improvement of new toolsets and approaches, such as biotechnology, metabolic engineering, process intensification, as well as integrated valorization strategies – especially liquid-phase catalysis or bio-oil upgrading systems - have brought biorefineries into the mainstream of the circular bioeconomy (de Jong & Jungmeier (2015).

From all the biomass feedstocks evaluated for biorefinery applications, algae is one of the most promising platforms with high tank productivity and environmental sustainability. Algae are photosynthetic entities with the potential for fast biomass profiles, possible carbon dioxide sequestration and good growth performance under the different environmental conditions during cultivation without heavy competition pressures on arable land or freshwater resources (Katiyar et al., 2021; Sarwer et al., 2022). All these features makes algal biomass a potential feedstock for future biorefinery development and continues support the notion of its sustainability against land availability constraints.

The algal biorefinery concept relies on the integrated and sequential valorization of algal biomass with high-value products, which not only allows more revenue generation but also reduces any residual waste. Like a petroleum refinery system, algal biorefineries utilize fractionation and cascade utilization strategies to separate and recover biomass components based on their biochemical signatures. Those lipid-rich fractions are usually produce clearly biodiesel and other biofuels; while those high carbohydrate fractions were normally fermented to bioethanol. Anaerobic Digestion: conducted on processed residual biomass to produce biogas following enhanced energy recovery and an increase in the process efficiency (Bello, 2024).

These integrated processing strategies not only offer advantages in terms of techno-economic viability but also assist the evolution towards zero-waste production systems. Apart from bioenergy applications, algal biomass is a rich source of diverse high-value compounds with wide-ranging industrial relevance. Microalgae, are known to produce proteins, essential amino acids, polyunsaturated fatty acids (PUFAs), vitamins and functional lipids for use within nutraceuticals, pharmaceuticals in food and feed products(Kamm & Kamm 2004). Additionally algae are a provider of commercially valuable pigments and antioxidants, such as chlorophylls, carotenoids, astaxanthin and phycobiliproteins, with broad applications in cosmetics, functional foods, natural colorants and health promoting compositions (Bello, 2024).Co-production has a significant positive economic impact and increases the commercial attractiveness of algal biorefineries. While notable advances have been made in the technology of various components of algal biorefineries, large- scale deployment currently faces hurdles related to cultivation costs, harvesting efficiency, downstream processing and energy use, as well as commercial limitations (Cherubini 2010). Hence, current research focuses on developing integrated biorefinery platforms combining advanced cultivation technologies, optimized biomass fractionation and sustainable conversion processes to enable economically viable and environmentally benign production systems. Therefore, algal biorefineries are receiving more attention towards a circular bioeconomy and future low-carbon industrial transitions.

Table 1. Major Industrial Biorefineries: Feedstock Sources, Conversion Technologies, and Product Outputs

Biorefinery producers	Source	Technologies	Product	Reference
USA	Corn stover	Lignocellulosic biorefinery	Cellulosic ethanol, lignin	Cherubini (2010)
Brazil	Bagasse and straw	Lignocellulosic biorefinery	Cellulosic ethanol	Cherubini (2010); Balan (2014)
USA	Agricultural residues	Biochemical conversion	Cellulosic ethanol, biochemicals	Cherubini (2010); Aro & Fatehi (2017)
Canada	Municipal solid waste (MSW)	Thermochemical biorefinery	Methanol, ethanol, renewable chemicals	Karatzos et al. (2014)

China	Industrial waste gases	Gas fermentation biorefinery	Ethanol, sustainable aviation fuel intermediates	Köpke et al. (2011); Liew et al. (2022)
Norway	Wood biomass	Forest biorefinery	Lignin products, bioethanol, specialty cellulose	Ragauskas et al. (2006)
Finland	Crude tall oil	Forest biorefinery	Renewable diesel, naphtha, chemicals	UPM Biofuels
Italy	Cardoon and agricultural biomass	Integrated biorefinery	Bioplastics, bio-lubricants, bio-intermediates	Parisi (2018)
USA	Corn grain	Grain biorefinery	Ethanol, animal feed, corn oil, biochemicals	Renewable Fuels Association (RFA)

2. TYPES OF ALGAL BIOREFINERIES

2.1 Microalgal Biorefinery

A microalgal biorefinery is a sustainable, integrated processing system that uses microscopic photo- synthetic organisms like *Nannochloropsis*, *Spirulina platensis*, and *Chlorella vulgaris* to create several bio-based products from a single biomass source. Due to their rapid growth rates, high photosynthetic efficiency and ability to accumulate large amounts of carotenoids, proteins, carbohydrates, pigments and other bioactive compounds; these microalgae have been considered potential bio factories. Unlike traditional crops, where freshwater is often needed, microalgae can be cultivated in saline water or even waste-water and refers less land (Wang et al., 2024) for cultivation as they could grow easily in controlled photobioreactors or open ponds.

Recent studies emphasize that the co-production of biofuels and high-value bioproducts through an integrated microalgal biorefinery is essential for achieving economic sustainability and supporting the transition toward a circular bioeconomy (Singh et al., 2024; Ezhumalai et al., 2024). Algal biorefineries are designed to extract and transform different algal components into a range of useful products through a variety of processes (Chandra et al., 2019; Katiyar et al., 2021). To achieve economically viable and sustainable algal biorefineries, a number of significant challenges must be addressed, including the optimization of algae cultivation, improvements in extraction and conversion technologies, and the integration of various operations to achieve overall process efficiency (Singh et al., 2025).

2.2 Macroalgal (Seaweed) Biorefinery

Macroalgal biorefineries represent an integrated biomass-processing approach that utilizes large marine algae, including brown seaweeds such as *Laminaria*, green seaweeds such as *Ulva*, and red seaweeds such as *Gracilaria*, to produce a range of biofuels and value-added bioproducts (Torres et al., 2024). Due to the advantage of avoiding direct competition with terrestrial food crops (driven by their land requirement) and minimising environmental impacts associated with cultivation such as freshwater and synthe- tic fertilisers, macroalgae have garnered much attention. In addition, seaweeds exhibit rapid growth rates and possess a high carbo- hydrate content, including polysaccharides such as laminarin, mannitol, cellulose, agar, alginate, and carrageenan, which can be efficiently converted into renewable energy and biochemicals.

Macroalgae are harvested much easier, with less energy input than microalgae, mainly because of the amount of biomass produced and that most macroalgae are cultivated in coastal marine environments. Under a biorefinery scheme, seaweed biomass carbohydrate fractions can be fermented to bioethanol and residual biomass digested for biogas. Outside of the biofuels area, macroalgae are significant industrial sources of hydrocolloids (radial fibres) such as agar from *Gracilaria*, alginate from *Laminaria* and carrageenan from different red algae which can be extensively used for gelling, thickening and stabilizing agents in food, pharmaceutical, cosmetic, and biotechnology industries. Seaweed-derived compounds are also incorporated into food

and feed additives owing to their high nutritional value, mineral content, dietary fibers, and bioactive molecules with antioxidant and antimicrobial properties (Cherry et al., 2024; Rajesh Banu et al., 2025).

2.3 Whole-Biomass Biorefinery

Among these pathways, the whole-biomass biorefinery is considered one of the most advanced and sustainable methods to valorize algal biomass in a more material-efficient method through sequential extraction and conversion processes that minimize waste while maximizing product recovery. The process mainly includes lipid extraction for biodiesel and bio-based chemicals, protein recovery (food, feed, nutraceutical, pharmaceutical). The residual fraction, rich in carbohydrates is separately fermented/hydrolysed into bioethanol, biohydrogen and other chemicals. Finally, residual biomass is employed by anaerobic digestion or composting to generate biogas (biofuels) and biofertilizers (soil amendments), creating no waste.

One of the big advantages is that this approach enables maximum using of available resources and make algal processing more economically and environmentally sustainable. It beneficial to solve the high production basis challenge of algal biofuel commercialisation by obtaining large amounts of high-end products simultaneously with biofuels (Wang et al., 2024). Cascading biomass not only reduces waste and environmental impacts, but it increases the diversity of products produced and thereby their sales. Further integration of energy recovery improves process efficiency and aligns with the principles of circular bioeconomy (Bello et al., 2024). Complete-biomass biorefineries are emphasised as critical points for a successful transition to an industrial-scale algae sector, with the potential of increasing efficiency while at once reducing greenhouse-gas emissions and ensuring that cuing two birds with one stone contributes effectively towards sustainable raw-material production of fuels, chemicals, food ingredients and agricultural inputs (Singh et al., 2025).

2.4 Integrated Wastewater-Based Biorefinery

The sustainable algal production system is an integrated wastewater-based biorefinery, in which microalgae are grown with municipal, agricultural or industrial wastewater through dual-use of wastewater treatment and biomass valorisation. Wastewater provide nutrient nitrogen, which includes phosphorus and organic carbon of algal growth . Algae can assimilate these nutrients and as such remove pollutants, reduce eutrophication, mitigate poor water quality due to lack of nutrient re- cycling and convert waste to biomass, establishing a circular resource recovery chain. This integrated low-cost system could reduce freshwater and nutrient inputs, as well as costs related to waste water management (Alhajeri et al., 2024).

This biomass can then be converted into a number of products, including lipid-rich biomass for biofuels (biodiesel and biogas), residual biomass for biofertilizers, or protein-rich biomasses which can be used as animal feed. They are aligned with principles of circular bioeconomy by allowing waste treatment, nutrient recycling, carbon capture and biomass production in the same biorefineries. Recent studies report high nutrient removal efficiency and economic potential, while advances in photobioreactors, harvesting, and downstream processing continue to improve scalability and commercial feasibility (Gonçalves et al., 2025).

2.4.1 Algal Biorefinery Production Process

The process of an algal biorefinery includes integrated stages for the conversion of biofuels and value-added products from algal biomass in a zero waste scenario. These processes start with the growth of microalgae or macroalgae in open ponds, photobioreactors or wastewater- based systems where algae consume sunlight and CO₂ as well as nutrients to produce biomass. This biomass is then harvested via flocculation, centrifugation, filtration or sedimentation, followed by dewatering and then pretreatment to enhance extraction (mechanical/chemical/thermal/enzymatic). The following steps allow to recovery lipids, proteins, carbohydrates, pigments and other bioactive compounds (Wang et al., 2024; Bello et al., 2024).

Lipids from the fruit are transformed into biodiesel, carbohydrates into bio methanol and bio-based chemicals, proteins into food, feed, pharmaceuticals or nutraceuticals products and pigments for cosmetic or health application after fractionation. Algae cultures and Cultivated Biomass Self-supply Residual biomass are more processed by anaerobic digestion—biogas, gasification or composting—biofertilizers and soil amendments, achieving nearly complete use of the biomass. This cascading approach improves resource efficiency, economic viability, and supports circular bioeconomy principles, while advances in cultivation and processing technologies continue to strengthen the commercial potential of algal biorefineries (Ezhumalai et al., 2024; Chavan et al., 2024).

Table 2. Classification of Algal Biorefineries Based on Feedstock Utilization, Conversion Pathways, and Major Products

Algal Biorefinery Type	Feedstock	Main Conversion Route	Major Products	Characteristics	Reference
Biofuel-Oriented Biorefinery	Microalgae/Macroalgae	Lipid extraction, transesterification, anaerobic digestion	Biodiesel, bioethanol, biogas, biohydrogen	Focuses primarily on energy production	Kamm et al. (2010)
High-Value Product Biorefinery	Microalgae	Extraction and purification	Pigments, antioxidants, nutraceuticals, pharmaceuticals	Targets high-value compounds for improved economics	Chisti (2007)
Integrated Algal Biorefinery	Whole algal biomass	Sequential extraction and conversion	Biofuels, proteins, pigments, fertilizers, chemicals	Maximizes biomass utilization through multiple product streams	Wijffels & Barbosa (2010)
Thermochemical Biorefinery	Algal biomass residues	Pyrolysis, gasification, hydrothermal liquefaction	Bio-oil, syngas, biochar, renewable chemicals	Suitable for wet or residual biomass	Nagarajan (2020)
Biochemical Biorefinery	Carbohydrate-rich algae	Fermentation, enzymatic hydrolysis	Bioethanol, organic acids, bioplastics precursors	Utilizes carbohydrates and proteins efficiently	Nagarajan et al. (2020)
Wastewater-Based Algal Biorefinery	Algae cultivated in wastewater	Nutrient recovery and biomass valorization	Biofuels, fertilizers, animal feed	Combines wastewater treatment with resource recovery	Gonçalves et al. (2021)
Circular Algal Biorefinery	Algal biomass and process residues	Cascade utilization and recycling	Bioenergy, fertilizers, biochemicals, biomaterials	Emphasizes zero-waste and circular economy principles	
Carbon Capture Integrated Biorefinery	Microalgae using industrial flue gas CO ₂	Photosynthetic carbon fixation and downstream processing	Biomass, biofuels, biochemicals	Simultaneously captures CO ₂ and produces valuable products	Nagarajan et al. (2020)

Table 3. Comparison of Major Algal Biorefinery Approaches

Biorefinery Approach	Feedstock Examples	Key Advantages	Major Products	Reference
Microalgal	Nannochloropsis, Spirulina platensis, and Chlorella vulgaris	Quick growth rates, high photosynthetic efficiency, and growth on non-arable land	Lipids, proteins, carbohydrates, pigments, and bioactive substances	Wang et al., 2024
Macroalgal (Seaweed)	Laminaria (brown), Ulva (green), and Gracilaria (red)	Does not require arable land, freshwater, or synthetic fertilizers; easier to harvest	Bioethanol, biogas, and hydrocolloids such as agar, alginate, and carrageenan	Torres et al., 2024; Cherry et al., 2024
Whole-Biomass	Entire algal material processed sequentially	Maximizes resource utilization, reduces waste, and improves sustainability	Biodiesel, bioethanol, biohydrogen, biogas, and biofertilizers	Wang et al., 2024; Bello et al., 2024; Singh et al., 2025
Integrated Wastewater	Algae cultivated in municipal, agricultural, or industrial wastewater	Treats wastewater, recovers nutrients, and lowers freshwater and operational costs	Biofuels, fertilizers, and protein-rich animal feed	Alhajeri et al., 2024; Gonçalves et al., 2025

2.5 Techno-Economic and Life Cycle Challenges

Algal biorefineries have tremendous potential but face serious techno-economic and life cycle bottlenecks preventing commercialization. Dewatering and harvest continue to be the most expensive energy intensive process, needed for concentrating highly dilute microalgae suspensions into a usable slurry (Soomro et al., 2016). Conventional mechanical and chemical approaches are energetically (and economically) costly, yet novel combinations such as bio flocculation followed by tangential flow filtration can reduce this total energy requirement down to about 0.041 kWh of biomass produced per kg (Soomro et al., 2016).

In contrast, the recovery is highly dependent on how conditions are set at different steps in thermochemical processing. More efficient for wet biomass, hydrothermal liquefaction provides biocrude 39–54% on dry weight basis (Li et al., 2017). Yet, high ash content and cyclical humidity can hinder the conversion efficiency as well as promote repolymerization at temperature peaks (Cheikhwafa et al., 2024). Amongst others, these life cycle assessments acknowledge consistent functional units; the scoping of feedstock supply modelling as insecure; and a lack techno-economic standardization in integration remain major limitations to commercial-scale viability (Soomro et al., 2016).

2.6 Harvesting and Dewatering

In algal biorefineries, harvesting and dewatering are critical downstream steps to separate algal biomass from the growth medium and reduce water content for subsequent processing stages. Stages involving harvesting and washing are particularly cost-contributing in the production of algal cultures due to low biomass concentrations. Flocculation (aggregating cells for separation), centrifugation (via biomass sedimentation at high g forces; fast but energy-intensive process) and filtering systems represent some of the most common harvesting methods (Filtration has proven costly due to fouling, packing costs and membrane replacement). Sedimentation is a low cost alternative culture, any emulsion from microalgae isolation. But it can be less effective than other solutions are suggested only when small in microorganisms. Industrial applications tend to combine these methods in order to achieve the maximum separation efficiency, while decreasing power consumption. Harvesting and dewatering are crucial to economic feasibility, sustainable energy balance and product compose yield in outline algal biorefineries (Bello et al., 2024; Wang et al., 2025; Chavan et al.) Integrated Process Scheme of the Algal Biorefinery is given in figure 1

Table 4. Algal Harvesting and Conversion Technologies

Processing Stage	Technology	Characteristics & Function	Reference
Harvesting & Dewatering	Flocculation, Centrifugation, Filtration, Sedimentation	Critical for reducing water content; combined to improve recovery efficiency and energy use	Bello et al., 2024; Wang et al., 2024; Chavan et al., 2024
Biochemical Conversion	Fermentation	Converts carbohydrate-rich fractions into bioethanol and other organic acids	Arora et al., 2021
Biochemical Conversion	Anaerobic Digestion	Breaks down organic matter under oxygen-free conditions to generate biogas, mainly methane and CO ₂	Narayan, 2024
Thermochemical Conversion	Pyrolysis	Converts algal biomass into bio-oil via thermal decomposition under oxygen-limited conditions	Kumar et al., 2017
Thermochemical Conversion	Hydrothermal Liquefaction	Converts wet biomass directly into biocrude under high temperature and pressure, reducing drying needs	Kumar et al., 2017
Thermochemical Conversion	Gasification	Produces syngas (hydrogen and carbon monoxide) which can be upgraded into fuels and chemicals	Kumar et al., 2017

2.7 Biomass Processing

Biomass processing is the core stage of an algal biorefinery, where harvested algal biomass gets fractionated into bio- chemical components and further micronized into saleable products. Microalgae can transport large amounts of oils appropriate for energy and nutraceutical applications, so lipid extraction is one of the major pathways. Solvent extraction is the most common method; it uses organic solvents for lipid separation, while supercritical fluid extraction (SFE) often utilizes a super-critical CO₂ as solvent that makes this technology faster and cleaner since no water or harmful residues will be left in product application. The extracted lipids are subsequently utilized as biodiesel feed- stock and can also serve as a source of high-value compounds such as omega-3 fatty acids. However, on its part, carbohydrate-rich fractions are hydrolyzed to yield fermentable sugars from the complex carbohydrates and biotechnologically fermented ultimately yielding bioethanol and other organic acids useful in industries (Arora et al. 2021)

The recovery of protein is another crucial part, when it comes to the valorization of biomass in algal biorefineries. Residual biomass remaining post lipid extraction typically contains significant amounts of proteins which can be harvested and converted into high-value products. It has been used to produce proteins that are useful for poultry, aquaculture (fish and crustaceans), or can even be incorporated into human food in the form of nutritional supplements. The integrated use of lipids, carbohydrates and proteins enhances the efficiency of resource utilization while minimizing waste in processes the technoeconomic viability

and sustainability of algal biorefinery systems. Such cascading utilization of biomass is one example how the principles of circular bioeconomy can be maintained by higher product extraction from a single feedstock (Sarwer et al., 2021).

2.8 Product Conversion

Through biomass fractionation, conversion technologies transform algal-derived intermediates into energy carriers and biobased chemicals. Thermochemical conversion processes are commonly used for biomass utilization because of their ability to process various compositions of biomass. Pyrolysis is thermal degradation of algal biomass which yields bio-oil under sub-stoichiometric conditions for oxygen, while gasification gives syngas a mixture that mainly contains hydrogen and carbon monoxide compounds (Kumar et al., 2017). Hydrothermal liquefaction is favourable for wet algal biomass which can be directly converted to biocrude at high temperature and pressure reducing the requirement of energy intensive drying steps. In addition to thermochemical pathways, biochemical conversion routes can also complement the possibilities for sustainable production. Fermentation is a process that converts carbohydrate-dense fractions into ethanol, while anaerobic digestion degrades biomass in oxygen-free conditions to produce biogas – mostly methane and carbon dioxide (Narayan 2024).

Table 5. High-Value Algal Bioproducts and Their Industrial Applications

Product Category	Specific Compounds	Industrial Applications	Reference
Nutritional & Functional	Proteins, essential amino acids, PUFAs, and vitamins	Nutraceutical, pharmaceutical, food, and feed industries	Kamm & Kamm, 2004; Koller et al., 2014
Pigments & Antioxidants	Chlorophylls, carotenoids, astaxanthin, and phycobiliproteins	Cosmetics, natural colorants, functional foods, and health-promoting formulations	Bello, 2024
Hydrocolloids	Agar, alginate, and carrageenan	Gelling, thickening, and stabilizing agents in food, pharmaceutical, and biotechnology industries	Cherry et al., 2024
Biofuels & Energy	Biodiesel, bioethanol, biogas, and biohydrogen	Renewable energy production and future low-carbon transitions	Bello, 2024; Wang et al., 2024

3. MAJOR ADVANTAGES OF ALGAL BIOREFINERIES

The major advantages of algal biorefineries include efficient utilization of biomass, reduced waste generation, lower greenhouse gas emissions, and the ability to produce multiple high-value products within a single integrated process. In contrast to traditional biofuel systems, algal biorefineries allow for recovery of lipids, proteins, carbohydrates and pigments along with residual biomass for improved economic and environmental sustainability. These products mainly include biofuels (biodiesel, bioethanol and biogas), proteins for food/feed/nutraceuticals, pigments or other bioactive compounds that find a wide application in pharmaceuticals or cosmeceuticals, as well as biofertilizers generated from residual biomass. These diverse outputs support the bioeconomy by promoting renewable energy production, nutrient recycling, carbon capture, waste valorization, and reduced dependence on fossil-based resources, thereby contributing to a circular and sustainable economic system (Wang et al., 2024; Bello et al., 2024).

Current world production of microalgal biomass is about 19000 tons per year, corresponding to approximately USD 5.7 billion, and the number of products derived from microalgae in food industry are increasing (Jacob-Lopes et al., 2018). The production of valuable compounds by microalgae, such as carotenoids, antioxidants, polyunsaturated fatty acids (PUFAs), proteins, lipids, carbohydrates and pigments provides scientific support in food and beverage as well as cosmetic, pharmaceutical and nutraceutical applications (Sidari & Tofalo, 2019). These supports are likely to further improve the bioproduction of high-value

products as well as biomass and biofuels with concomitant advances in genetic/metabolic engineering (Leu & Boussiba, 2014; Chew et al., 2017; Levasseur et al., 2020), while targeting high value compounds over environmental applications becomes one route towards economic viability.

According to Koller et al. Algae oil rich in polyunsaturated fatty acids, which are necessary for the human metabolism, possess high commercial potential as raw materials to be used in pharmaceuticals, medicine and health foods (2014). These are also more useful than biofuel. In addition to biofuels, microalgae are used in the production of different products such as polymers, dietary supplements and

evidence of their applicability as a bioresource exhibited through protein purification via structure-aided drug design (Chew et al.; Koyande, 2017). Optimization and integration of production processes are necessary to maximize the use of microalgae, especially if these align with a biorefinery model that can provide sustainable as well as economic outputs (Chen et al., 2010).

4. ADVANCED METABOLIC ENGINEERING AND SYNTHETIC BIOLOGY

Beyond optimizing cultivation and downstream processing, recent advancements in synthetic biology have emerged as a transformative frontier for algal biorefineries. Utilizing precision genome-editing tools like CRISPR/Cas9, researchers can selectively rewire microalgal metabolic pathways to overcome natural physiological limitations (Dhokane et al., 2023). Metabolic flux is fundamentally in the balance and can be redirected to strongly ameliorate partitioning of carbon toward desired valuable targets simply by knocking out competitive pathways or overexpressing key enzymes (Sreenikethanam et al., 2022).

For example, the ability of engineering targets is evident by increasing in intracellular lipid accumulation from 0–70% dry cell weight at baseline (Dhokane et al., 2023) thereby significantly reducing downstream biofuels extraction costs. In addition, precision engineering enables the hyper-accumulation of high-value biobased products such as astaxanthin, phycocyanin and target polyunsaturated fatty acids which makes algal host a highly reliable bio factory (Dhokane et al., 2023; Sreenikethanam et al., 2022). Integrating these metabolically engineered strains into the whole-biomass biorefinery pipeline optimizes the product portfolio and represents a critical leap toward commercial viability.

5. CONCLUSION

Algal biorefineries are an integrated and sustainable method for the conversion of algal biomass into biofuels and other high-value bioproducts with low waste generation. Utilizing cutting-edge technologies for growing, harvesting, and converting biomass, algal biorefineries throw traction to resource use efficiencies, greenhouse gas (GHG) abatement credits and circular bioeconomy avenues. Their potential as a new renewable alternative to fossil-based industries lies in their ability to be produced into renewable energy, food ingredients, chemicals, and agricultural products. This review gives an extensive overview of algal biorefinery categorization, production approaches, end-products and applications in the bioeconomy. The purpose is to showcase recent technological advances, discuss existing challenges and opportunities and highlight the contribution of these integrated algal biorefineries in sustainable resources utilization for industrial-scale bio-based production. (Kumar et al., 2017)

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AUTHOR CONTRIBUTIONS

Ganga G. and Vishnu S. L. conceptualized the review, outlined the structure, and drafted the initial manuscript. Lakshmi Gopidas, Subhash S. K., Remya A. S., Nisha V. S., and Jisha S. contributed to the literature review, data synthesis, and manuscript editing. All authors read and approved the final manuscript.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

ETHICS STATEMENT

Not applicable. As a review article, this study did not involve new research on human participants or animal subjects.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new datasets were generated or analyzed during the preparation of this review.

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