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Marine microalgae as a renewable energy resource: Advances, technoeconomic insights, and commercialization pathways

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ABSTRACT

Marine microalgae are increasingly recognized as a potential feedstock for addressing energy challenges due to their high growth rates, efficient photosynthetic conversion of nutrients into diverse bioactive metabolites. Their biological importance extends beyond their ecological function as primary producers in marine habitats. Other lipids, carbs and proteins are encouraging factors for high-caloric production of biofuels such as biodiesel, bioethanol, biogas and biohydrogen using marine microalgae as feed stocks. Their relevance in this field was further solidified with their ability to capture CO_2 and remediate wastewater. Its potential has been recognized; however, there are great hurdles to large-scale commercialization, including expensive production, energy-demanding harvesting methods and technological barriers to bioreactor design. Current challenges highlight the need for new tools and approaches such as genetic engineering, cultivation techniques, and biorefinery advances. This review aims to offer an extensive discussion on the state-of-the-art applications of marine microalgal biomass for sustainable energy production and addresses the present challenges, with an emphasis on future perspectives. The results indicate that, if sufficient research, investment and policy support is provided, marine microalgae could be at the forefront of the transition to a more sustainable and renewable future.

1. Introduction

1.1. What are marine microalgae and their diversity?

Marine microalgae are a diverse group of microscopic photosynthetic organisms that inhabit marine environments [1,2]. They include various taxonomic groups such as **cyanobacteria, diatoms, dinoflagellates, green algae, and haptophytes**, each possessing distinct physiological and biochemical characteristics. These unicellular organisms are fundamental components of marine ecosystems, contributing to primary production and forming the base of the aquatic food web. Unlike macroalgae (seaweeds), which are multicellular and often visible to the naked eye, microalgae are microscopic but exhibit exceptional adaptability to diverse environmental conditions [3].

Marine microalgae display remarkable metabolic versatility, enabling them to survive in extreme conditions, such as high salinity, varying temperatures, and limited nutrient availability [4]. Their diversity extends beyond taxonomy to include variations in pigment composition, nutrient assimilation strategies, and lipid production capacities. These unique attributes make marine microalgae an attractive target for biotechnological applications, particularly in sustainable energy production [5]. Recent studies have demonstrated the growing potential of marine microalgae as a sustainable bioresource due to their high photosynthetic efficiency and rapid biomass accumulation [6]. Industrial interest has increased following pilot scale demonstrations integrating microalgal cultivation with carbon capture from industrial flue gas streams. These systems highlight the potential of microalgae to simultaneously contribute to climate change mitigation and renewable energy production, strengthening their position as a next generation bioresource platform [7].

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1.2. Hierarchy of their ecological role and importance

Marine microalgae play a critical role in maintaining oceanic and global ecological balance. As primary producers, they contribute significantly to photosynthesis-driven carbon fixation, converting atmospheric carbon dioxide (CO_2) into organic compounds [8,9]. This process is essential in mitigating climate change by reducing atmospheric CO_2 levels, a major driver of global warming. Additionally, marine microalgae produce nearly 50% of the Earth's oxygen, highlighting their pivotal role in sustaining life on Earth [10,11].

Beyond carbon fixation, marine microalgae support marine food chains by serving as a primary food source for zooplankton, which in turn sustains higher trophic levels, including fish, marine mammals, and humans [12]. Their ability to synthesize bioactive compounds, including polyunsaturated fatty acids (PUFAs), carotenoids, and polysaccharides, further enhances their ecological importance, as these compounds contribute to the nutrition and health of marine organisms. Marine microalgae also play a significant role in biogeochemical cycling, particularly in the nitrogen and phosphorus cycles. They assimilate nitrogen and phosphorus from seawater, preventing excessive accumulation that could lead to harmful algal blooms (HABs) and eutrophication [13]. At the same time, their ability to absorb heavy metals and pollutants has made them a promising tool for bioremediation and environmental detoxification.

1.3. Interest of biotechnology and energy scientists in marine microalgae

The potential of marine microalgae extends beyond their ecological significance. In recent years, they have gained substantial attention from biotechnology, pharmaceutical, and energy researchers due to their rich biochemical composition [14,15]. Their high lipid content makes them a promising feedstock for biofuel production, offering a renewable and environmentally friendly alternative to fossil fuels [16,17]. Unlike terrestrial crops used for biofuels, such as soybean and palm oil, marine microalgae do not compete with food production and can be cultivated in saline waters, avoiding freshwater depletion [16,18,19]. Additionally, marine microalgae can be genetically engineered to enhance lipid accumulation, stress tolerance, and productivity, making them more suitable for large-scale biofuel applications [20,21]. Advances in synthetic biology and metabolic engineering have enabled researchers to manipulate algal genomes for improved biofuel yields and energy efficiency [22,23].

The pharmaceutical and nutraceutical industries have also explored marine microalgae for their bioactive compounds, including antioxidants, anti-inflammatory agents, and antimicrobial peptides. These compounds have shown potential applications in cancer therapy, neuroprotection, and immune system modulation. Furthermore, their ability to produce high-value metabolites, such as β-carotene, astaxanthin, and fucoxanthin, has made them valuable in functional foods and dietary supplements. Marine microalgae have also attracted interest in carbon capture and sequestration (CCS) technologies due to their ability to absorb CO_2 more efficiently than terrestrial plants [24,25]. Industrial applications are exploring the feasibility of integrating microalgae cultivation with wastewater treatment and CO_2 biofixation, reducing greenhouse gas emissions and mitigating environmental pollution [26,27]. The energy sector is particularly interested in microalgae as a sustainable energy source due to their ability to generate biohydrogen, biogas, and bioethanol through biochemical conversion processes. Their rapid growth rate, high photosynthetic efficiency, and adaptability to various cultivation conditions make them an attractive candidate for third-generation biofuels. However, despite their promising potential, economic and technological challenges remain barriers to widespread commercialization.

1.4. Aims and scope of the review

Although several reviews have explored microalgal biofuels, carbon capture potential, and bioproduct applications independently, a comprehensive synthesis specifically focused on marine microalgae integrating biological efficiency, multi sector industrial applications, and techno economic scalability remains limited. Many existing studies primarily emphasise freshwater microalgal biofuel systems or focus narrowly on single application domains such as lipid based biodiesel production or carbon sequestration. In addition, comparative evaluation of marine microalgal productivity, process feasibility, and sustainability metrics across multiple energy and industrial pathways is often fragmented. This review aims to address this gap by providing an integrated analysis of marine microalgal biology, energy applications, environmental benefits, and commercialization challenges within a unified sustainability and circular bioeconomy framework. By consolidating recent technological advances, productivity considerations, and future scale up strategies, this work provides a clearer translational perspective linking laboratory research, pilot scale development, and industrial implementation. The growing need for sustainable and renewable energy solutions has driven extensive research into marine microalgae as an alternative energy source [28]. This review aims to provide a comprehensive analysis of the biological significance, current applications, and future prospects of marine microalgae in sustainable energy. The study discusses the biological significance of marine microalgae, including their ecological role, photosynthetic efficiency, and biochemical composition. The review also examines the current applications of marine microalgae in sustainable energy production, focusing on biofuel production (biodiesel, bioethanol, biogas, and biohydrogen), carbon capture, and wastewater treatment and to identify key challenges and limitations in large-scale marine microalgae utilization, including economic feasibility, cultivation constraints, and technological bottlenecks. Explore future directions and emerging trends in marine microalgae research, such as genetic engineering, advanced bioreactor systems, and commercialization strategies. Through this review, we aim to bridge scientific insights and industrial applications, highlighting the feasibility and challenges of using marine microalgae as a sustainable energy resource. By evaluating current technological advancements and future prospects, we hope to provide a foundation for further research and industrial innovation in renewable energy and environmental sustainability.

1.5. Biodiversity and taxonomy

Marine microalgae comprise a highly diverse group of organisms that are classified based on their pigment composition, cell wall structure, and reproductive strategies [29,30]. The primary classes of marine microalgae include diatoms (Bacillariophyceae), dinoflagellates (Dinophyceae), cyanobacteria (Cyanophyceae), chlorophytes (Chlorophyceae), haptophytes (Haptophyceae), and raphidophytes (Raphidophyceae). Among these, diatoms are one of the most abundant and productive microalgae, characterized by their silica-based cell walls known as frustules. They significantly contribute to marine primary production and biogeochemical cycling. Diatoms are estimated to contribute nearly 20 percent of global primary productivity and play a major role in oceanic carbon cycling through silica based cell wall formation and sedimentation processes [31]. Coccolithophores such as *Emiliania huxleyi* contribute significantly to long term carbon sequestration through the formation of calcium carbonate plates, which can persist in marine sediments for geological timescales [32]. Dinoflagellates are recognized for their flagella-driven mobility and bioluminescence, though some species are notorious for forming harmful algal blooms (HABs) that impact marine ecosystems and human health. Cyanobacteria, despite being prokaryotic, play a vital role in nitrogen fixation and primary production in nutrient-poor oceanic regions [33,34]. Chlorophytes, which include green microalgae, are rich in chlorophyll *a and b* and play an essential role in nutrient cycling. Haptophytes, such as coccolithophores, influence oceanic carbon sequestration by forming calcium carbonate plates, while raphidophytes, though less common, contribute to toxic bloom formations in coastal waters.

Marine microalgae have evolved unique physiological and biochemical adaptations that enable them to survive in diverse oceanic environments. Their photosynthetic efficiency is enhanced by accessory pigments like fucoxanthin, phycoerythrin, and phycocyanin, which optimize light absorption in low-light conditions, such as deep-sea environments [35,36]. Some microalgae species, such as *Dunaliella*, exhibit osmoregulatory mechanisms by accumulating glycerol and other compatible solutes to maintain cellular balance in high-salinity conditions [37,38]. Diatoms utilize silicon to construct their intricate cell walls, contributing to the marine silicon cycle [37,38], while coccolithophores incorporate calcium carbonate into their exoskeletons, playing a crucial role in global carbon dynamics [39,40]. Additionally, certain dinoflagellates and raphidophytes produce potent neurotoxins, including saxitoxins and brevetoxins, which can negatively affect marine organisms and human populations [41,42].

1.6. Climate modelling and carbon sequestration

Marine microalgae play a significant role in regulating the Earth's climate through carbon sequestration (Fig. 1). Their contribution to the biological carbon pump is vital in mitigating atmospheric CO_2 levels [24,43,44]. During photosynthesis, marine microalgae absorb CO_2 from seawater and convert it into organic matter, which is subsequently transferred to deeper ocean layers through sedimentation and consumption by zooplankton. This natural process reduces the concentration of atmospheric CO_2, mitigating the effects of climate change. Coccolithophores further contribute to long-term carbon storage by forming calcium carbonate shells that settle on the ocean floor, where they remain for millions of years [39,45]. The biological carbon pump driven by marine microalgae represents one of the largest natural carbon sequestration mechanisms on earth [46]. Microalgae fix atmospheric carbon dioxide through photosynthesis and transfer organic carbon to deeper ocean layers via trophic transfer and sedimentation processes [47].

Additionally, certain marine microalgae release dimethyl sulfide (DMS), a compound that influences cloud formation and global climate regulation [48]. DMS emissions contribute to the formation of sulfate aerosols, which increase cloud reflectivity and, in turn, lower global temperatures [49,50]. This process acts as a natural climate feedback mechanism that counterbalances the effects of greenhouse gas emissions.

Compared to terrestrial plants, marine microalgae exhibit higher photosynthetic efficiency. Unlike land plants, which allocate significant energy toward structural development (e.g., roots and stems), microalgae direct most of their energy toward biomass production [44,51]. Certain species, such as *Chlorella* and *Nannochloropsis*, have rapid growth rates, with the ability to double their biomass in just a few hours [52–54]. These species are increasingly being evaluated for integration into industrial carbon capture and utilization frameworks. This superior adaptability to environmental changes allows microalgae to efficiently adjust their metabolism in response to fluctuations in light intensity and nutrient availability, further optimizing their photosynthetic performance.

1.7. Biochemical composition

Marine microalgae are rich in valuable biochemical compounds,

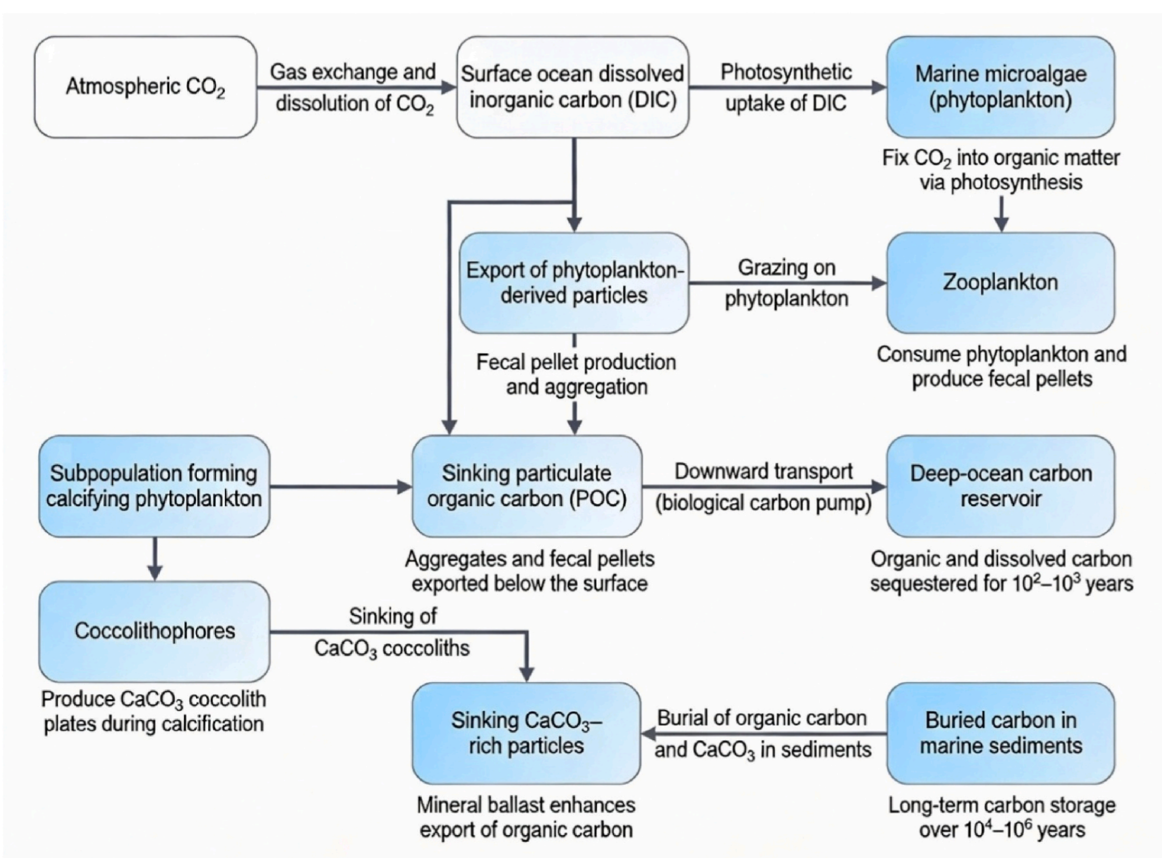

Fig. 1. Marine microalgae in carbon sequestration and the biological carbon pump.

making them highly beneficial for food, pharmaceuticals, and biofuel production [5,14,15,55] (Fig. 2). Their biochemical composition primarily consists of lipids, carbohydrates, and proteins, each of which serves various industrial applications. Many marine microalgae, such as *Nannochloropsis* and *Isochrysis*, accumulate high levels of polyunsaturated fatty acids (PUFAs), including omega-3 and omega-6, which are essential for human health [56]. These lipids are widely used in dietary supplements, pharmaceuticals, and aquaculture feeds [57,58]. *Nannochloropsis* species are known for high omega 3 fatty acid production, particularly eicosapentaenoic acid, which has applications in nutraceutical and pharmaceutical industries [59]. *Haematococcus pluvialis* is commercially exploited for astaxanthin production due to its strong antioxidant properties [60].

Microalgal carbohydrates also hold significant commercial value. Many species produce polysaccharides, including starch and sulfated polysaccharides, which find applications in the food and medical industries [61].

Marine microalgae also produce various high-value bioactive compounds with promising applications. Carotenoids such as astaxanthin (from *Haematococcus*), fucoxanthin (from diatoms), and lutein are known for their potent antioxidant and anti-inflammatory properties [14,62–64]. Phycobiliproteins, found in cyanobacteria, are widely used as natural food colourants and fluorescent markers in biomedical research [65,66].

2. Sustainable energy: recent use cases

The transition to sustainable energy sources has become a focal point in global energy policies. As fossil fuel reserves continue to deplete and carbon emissions exacerbate climate change, researchers and industries have turned toward renewable and environmentally friendly energy alternatives. Sustainable energy encompasses various innovative technologies that integrate biofuel production, hydrogen generation, power-to-methanol processes, and wastewater-based biomass recovery [67,68]. These approaches not only reduce greenhouse gas emissions but also provide cost-effective and scalable solutions for energy production.

2.1. Biofuel production

Biofuels are renewable energy sources derived from organic matter, including plant and microbial biomass [69–71] (Fig. 3). The three primary categories of biofuels, biodiesel, bioethanol, and biogas, offer significant environmental benefits, such as reduced carbon emissions and waste valorization [72,73]. The development of biofuels has become increasingly important in addressing global energy demand, reducing dependence on fossil fuels, and lowering greenhouse gas emissions. In this context, marine microalgae have emerged as one of the most promising next generation biofuel feedstocks due to their unique biological and cultivation advantages [17]. Unlike conventional biofuel sources such as corn, sugarcane, and oilseed crops, marine microalgae exhibit significantly higher biomass productivity and faster growth rates, with some species capable of doubling biomass within hours under optimal conditions [74]. Microalgae cultivation does not compete with agricultural land used for food production, since they can be grown in marine environments, saline water, or wastewater systems. This reduces pressure on freshwater resources and supports sustainable land use strategies [75].

Marine microalgae also possess high lipid accumulation potential, making them highly suitable for biodiesel production, while their carbohydrate fractions can be utilized for bioethanol and biogas generation [76]. Beyond fuel production, their ability to capture carbon dioxide from industrial emissions strengthens their role in climate change

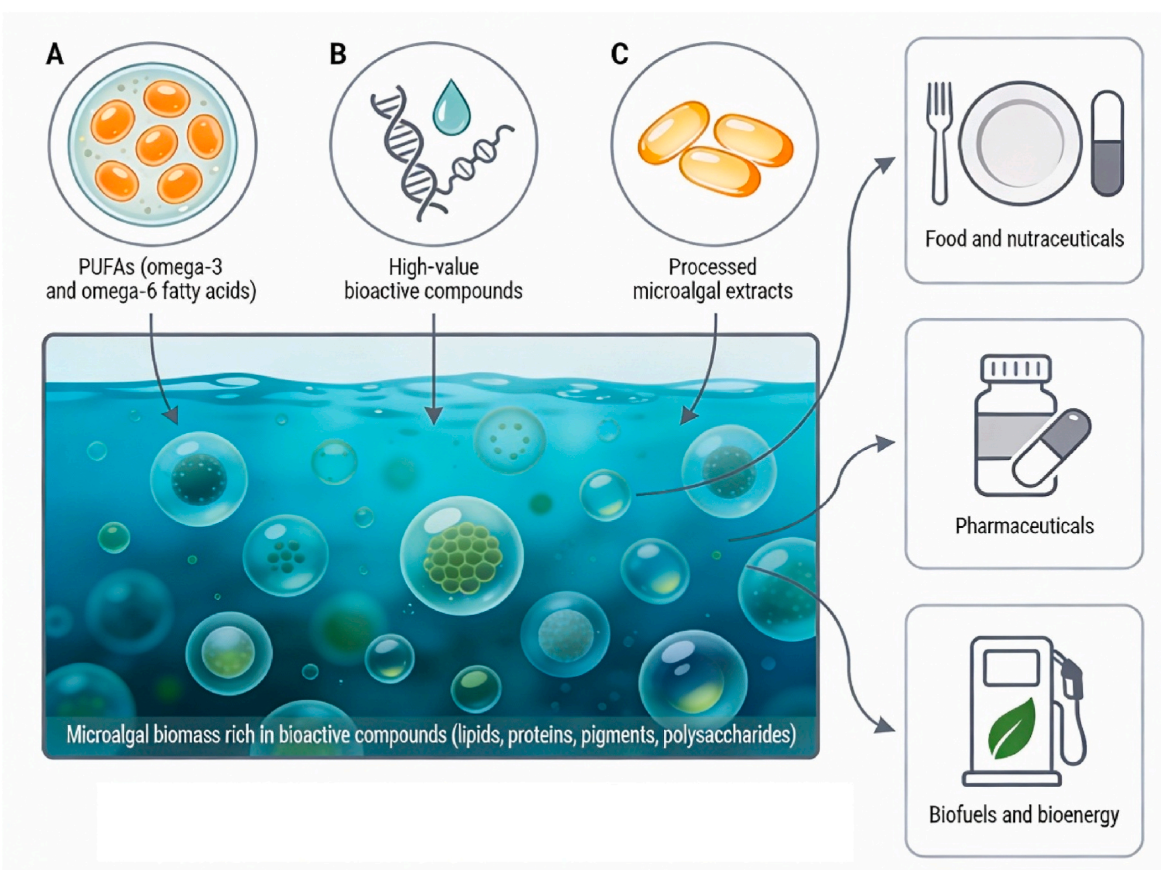

Fig. 2. Biochemical richness and industrial applications of marine microalgae.

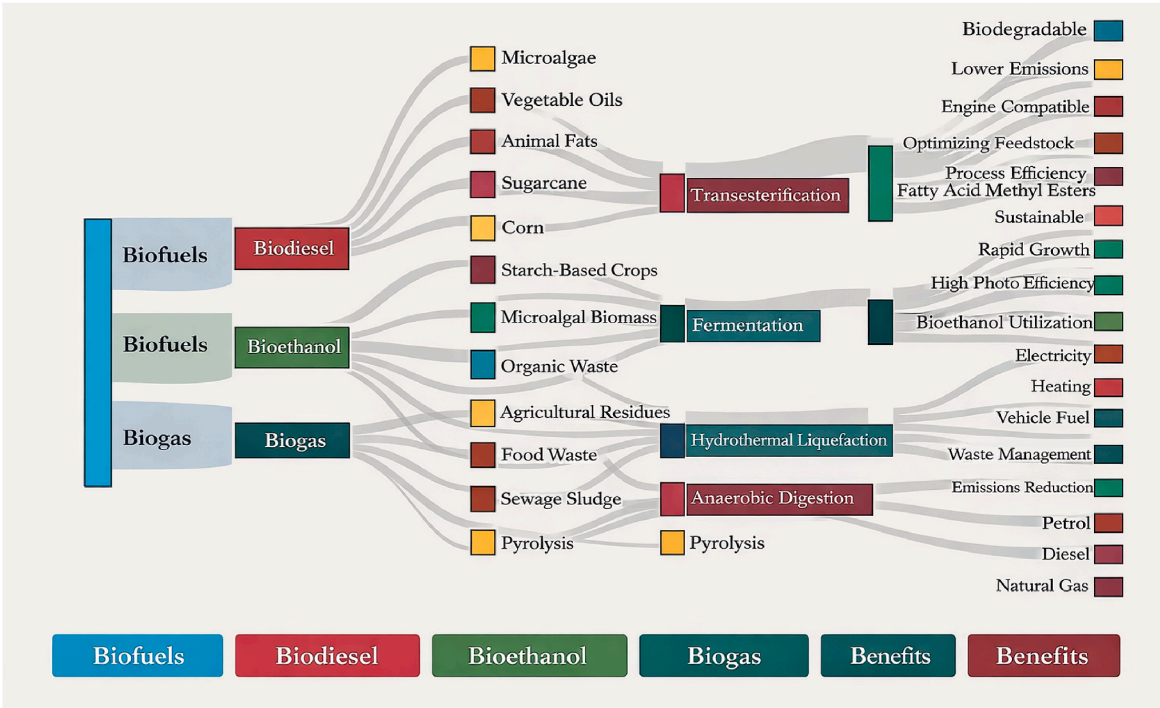

Fig. 3. Flowchart of biofuel categories, feedstocks, production processes, products, and benefits.

mitigation and supports circular bioeconomy frameworks. Their integration into biorefinery systems enables simultaneous production of fuels, biochemicals, and high value compounds, improving overall economic feasibility. These combined advantages position marine microalgae as a highly sustainable and scalable feedstock for future biofuel production systems [77]. To provide a comparative overview of marine microalgae based sustainable energy pathways and reported performance outcomes, representative studies are summarised in Table 1.

Biodiesel production involves the extraction of lipids from biological sources such as microalgae, vegetable oils, or animal fats, followed by a chemical process known as transesterification [86,87]. During this reaction, triglycerides are converted into fatty acid methyl esters (FAME), which can be used as a direct replacement for conventional diesel fuel. The advantages of biodiesel include its biodegradable nature [88], lower emissions of sulfur oxides and particulate matter [89], and compatibility with existing diesel engines [90]. However, the challenge remains in optimizing feedstock selection and processing efficiency to make biodiesel economically viable at an industrial scale [91–93].

Bioethanol, another critical biofuel, is produced through the fermentation of carbohydrate-rich biomass [10,94]. Traditionally, bioethanol is derived from sugarcane, corn, and other starch-based crops. However, recent advancements have explored microalgal biomass fermentation as a more sustainable alternative [95,96]. Microalgae exhibit rapid growth, high photosynthetic efficiency, and the ability to utilize carbon dioxide as a carbon source. Fermenting microalgal carbohydrates into ethanol can significantly enhance bioethanol production while minimizing land and water usage compared to conventional agricultural crops [94].

Biogas production, relies on the anaerobic digestion of organic waste, generating methane-rich gas that can be used for electricity generation, heating, and vehicle fuel. Anaerobic digestion breaks down

Table 1
Representative studies on marine microalgae based sustainable energy production pathways.

Marine Microalgal Species	Energy Type	Methodology	Key Outcomes	Key Significance	Reference
Nannochloropsis sp.	Biodiesel	Lipid extraction followed by transesterification	High lipid content (20 to 50 percent dry weight), strong biodiesel conversion efficiency	One of the most studied marine biodiesel candidates	[78]
Tetraselmis sp.	Biodiesel and Bioethanol	Integrated lipid extraction and carbohydrate fermentation	Dual energy recovery potential from single biomass source	Supports multi product biorefinery systems	[79]
Isochrysis sp.	Biodiesel and Bioproducts	High value lipid extraction followed by fuel conversion	Production of both fuel lipids and high value compounds	Improves techno economic feasibility	[80]
Phaeodactylum tricornutum	Biodiesel and Biohydrogen	Metabolic engineering and lipid enhancement strategies	Improved lipid productivity and biohydrogen potential	Strong model marine diatom for bioenergy research	[81]
Thalassiosira pseudonana	Bioethanol and Biodiesel	Genetic and metabolic pathway optimisation	Enhanced carbon fixation and biomass productivity	Model species for marine metabolic engineering	[82]
Dunaliella salina	Biodiesel	Stress induced lipid accumulation under hypersaline cultivation	High lipid productivity under controlled stress conditions	Demonstrates large scale salt based cultivation feasibility	[83]
Marine microalgal consortia	Biogas	Anaerobic digestion of mixed marine biomass	Stable methane production and substrate flexibility	Suitable for wastewater coupled marine bioenergy systems	[84]
Synechococcus marine strains	Biohydrogen	Photobiological hydrogen production via photosynthetic pathways	Renewable hydrogen generation potential	Emerging marine cyanobacterial hydrogen platform	[85]

organic matter, including agricultural residues, food waste, and sewage sludge, in oxygen-free conditions. The resulting methane content can be upgraded to biomethane, offering a renewable alternative to natural gas. In addition to energy production, biogas plants provide a sustainable solution for managing organic waste, reducing landfill emissions, and improving resource recovery [97].

Quantitative comparisons further highlight the potential advantages of microalgal biofuel systems relative to conventional terrestrial biofuel feedstocks. Marine microalgae can achieve biomass productivities typically ranging from approximately 20 to 50 g m^{-2} day^{-1} under optimised cultivation conditions, which is significantly higher than most terrestrial oilseed crops. For example, oil productivity from microalgae can reach several thousand litres per hectare per year, whereas soybean and palm oil systems typically produce substantially lower oil yields per unit cultivation area. In addition, microalgae can be cultivated in saline or wastewater environments, eliminating competition with agricultural land and freshwater resources. However, despite higher theoretical productivity, current large scale microalgal biofuel systems remain constrained by higher operational costs and energy intensive downstream processing requirements compared to mature terrestrial biofuel supply chains. These quantitative differences highlight both the productivity potential and the current economic challenges associated with marine microalgal biofuel commercialization.

Other biofuel production options from microalgae are integrated fuel and coproduct production through hydrothermal liquefaction (HTL), pyrolytic fractionation of biofuels from solvent-extracted crude lipids and pyrolytic lipid recovery and biofuel refining through direct pyrolysis of whole dry algae followed by oil refining. Petrol, diesel and natural gas fuel forms are possible through all the three aforementioned options. Hydrothermal liquefaction is touted as a promising option to recover biofuels from microalgae without the need for the resource-intensive drying step post-growth stage of algae. The oil recovery yield is high. However, the method still has significant scale-up and R&D challenges before it can become a viable downstream processing technology [98]. Crude algal lipids can be fractionated refined through petroleum refinery processes similar to fossil crude oil. Whole dry algae can be pyrolysed for lipid recovery. 35-50% bio-oil recovery by weight have been reported [99]. These intermediate-step bio-oils tend to have heating values, 30-35 MJ/kg that are lower than those of diesel and biodiesel, 35-40 MJ/kg. Need for further refining and development of co-products from the rest of the pyrolysed algal content mean that this process needs further developmental steps and have not yet been commercialized.

2.2. Hydrogen production

Hydrogen is increasingly recognized as a key component of the clean energy transition due to its high energy density and versatility in various applications, including fuel cells, industrial processes, and transportation [100]. There are multiple pathways for hydrogen production, with photobiological and enzymatic approaches gaining attention for their sustainability.

Photobiological hydrogen production utilizes photosynthetic microorganisms, such as cyanobacteria and microalgae, to convert solar energy into hydrogen gas. These microorganisms harness sunlight and water to drive biological hydrogen evolution, offering a renewable and carbon-neutral alternative to conventional hydrogen production methods, such as steam methane reforming. However, challenges related to low hydrogen yields and process scalability require further research to improve efficiency [101].

In addition to photobiological methods, hydrogen can be generated through enzymatic and metabolic pathways. This process involves using engineered microorganisms or isolated enzymes to catalyze hydrogen production from organic substrates. By optimizing metabolic pathways and genetic modifications, researchers have enhanced microbial hydrogen production rates. These approaches present a promising avenue for developing sustainable hydrogen production systems with minimal carbon footprint [102].

2.3. Power to methanol up to 10 GJ

Methanol is an essential chemical feedstock and fuel that can be synthesized using sustainable carbon sources. The power-to-methanol approach integrates carbon capture and utilization (CCU) to convert carbon dioxide into methanol, mitigating industrial carbon emissions while producing a valuable energy carrier [103].

Carbon capture and utilization (CCU) involves capturing CO_2 from industrial emissions and converting it into useful chemicals, such as methanol. This process not only reduces atmospheric CO_2 levels but also provides a sustainable route for methanol synthesis [104]. Renewable hydrogen generated from electrolysis can react with captured CO_2 in a catalytic process to form methanol. This approach supports circular economy principles by transforming waste carbon into a valuable commodity [105].

Microalgae-based CO_2 sequestration is another method employed in power-to-methanol applications. Microalgae can efficiently capture CO_2 from flue gases and industrial emissions, assimilating it into biomass. This biomass can then be processed into biofuels, bioplastics, and other bio-based products [106]. By integrating microalgal systems with industrial effluent management, companies can reduce their environmental impact while harnessing renewable carbon sources for energy production [107].

2.4. Using wastewater to treat and recover biomass

The integration of microalgal cultivation with wastewater treatment has demonstrated strong potential for nutrient removal and biomass generation. Wastewater contains organic nutrients, nitrogen, and phosphorus, which can be utilized by microorganisms and algae for growth. By integrating wastewater treatment with biofuel production, researchers have developed innovative systems that enhance resource recovery and sustainability [108]. Microalgae can effectively remove nitrogen and phosphorus from wastewater streams while producing biomass suitable for biofuel or bioproduct synthesis. This dual function approach supports circular bioeconomy frameworks and reduces operational costs of biomass production.

Another promising approach is uniting wastewater treatment with biofuel production. Anaerobic digestion of organic matter in wastewater generates biogas, which can be upgraded to biomethane and used as a renewable energy source [109]. Some of the biggest commercial algal raceway ponds (>1 ha) have been set up for wastewater treatment. Inorganic nutrients in wastewater are set up for assimilation in microalgae through photosynthetic growth which needs sunlight. This places a direct demand on land leading to low productivity. Productivity of 8 g/m2/day have been reported [98]. These operations tend to be much more maintenance-intensive than those of algal biofuels and algal food products. Such a system in the municipal wastewater treatment plant in Christchurch, New Zealand had reduction in Biological Oxygen Demand, ammoniacal nitrogen and dissolved reactive by 50%, 65% and 19% respectively [98]. A sewage treatment plant in Mysore, Karnataka, India also utilizes algae-based treatment. The plant treats 68 million litres of wastewater per day. It reports a consortia of algae and other microbes for treatment and the composition of the various algae and microbes change through the course of the treatment. Chemical Oxygen Demand and Biological Oxygen Demand reduced by 60% and 82%. Nitrogen removal was not found to be efficient during the 14-day residence time but reduction in total suspended solids was found to be significant [98].

To provide a broader overview of the technological scope and application potential of marine microalgal biomass, major application domains and representative research outcomes are summarised in Table 2.

Table 2
Major applications of marine microalgal biomass and key research outcomes.

Marine Microalgal Species	Application Area	Key Methodology	Major Findings/Outcomes	Industrial/Practical Significance	Reference
Nannochloropsis sp.	Biofuel and Nutraceuticals	Lipid extraction, omega 3 fatty acid recovery	High lipid yield and EPA rich oil production	Dual value biofuel and health supplement production	[110]
Tetraselmis sp.	Biofuel and Aquafeed	Integrated lipid extraction and biomass utilization	Balanced lipid and protein composition	Supports circular bioeconomy and aquaculture feed systems	[111]
Isochrysis sp.	Nutraceuticals and Biofuel	PUFA extraction and lipid conversion processes	High DHA and PUFA production	High value marine nutraceutical and energy feedstock	[110]
Phaeodactylum tricornutum	Biofuel and Carbon Capture	Metabolic engineering and CO2 biofixation studies	High carbon fixation efficiency and lipid accumulation	Model marine strain for bioenergy and carbon capture systems	[82]
Thalassiosira pseudonana	Carbon Sequestration and Bioenergy	Photosynthetic efficiency optimisation and genetic studies	High biomass productivity and carbon assimilation	Climate mitigation and bioresource platform potential	[112]
Dunaliella salina	Bioproducts and Biofuel	Stress induced metabolite and lipid production	High carotenoid and lipid accumulation	Commercial carotenoid production with biofuel potential	[113]
Skeletonema costatum	Wastewater Treatment and Biomass Production	Nutrient removal from marine wastewater	High nitrogen and phosphorus removal efficiency	Environmental remediation and biomass generation	[114]
Marine microalgal consortia	Biogas and Wastewater Treatment	Anaerobic digestion and mixed culture cultivation	Stable methane production and improved nutrient removal	Suitable for large scale wastewater integrated energy systems	[115]
Synechococcus marine strains	Biohydrogen and Carbon Capture	Photobiological hydrogen production and CO2 fixation	Renewable hydrogen production potential	Emerging clean marine biohydrogen platform	[116]

When compared with conventional renewable fuel feedstocks and alternative low carbon energy technologies, marine microalgae demonstrate several distinct advantages but also face important technological and economic challenges [17]. Unlike terrestrial biofuel crops such as soybean, palm oil, and corn, marine microalgae offer significantly higher areal productivity, faster growth rates, and do not compete with agricultural land or freshwater resources. In comparison with lignocellulosic biomass systems, microalgae cultivation enables direct carbon dioxide utilization and higher photosynthetic efficiency under controlled cultivation conditions [117]. However, competing technologies such as electrofuels, hydrogen from renewable electrolysis, and advanced waste to energy platforms currently demonstrate advantages in process maturity and infrastructure compatibility [118]. While microalgal systems show strong potential for integrated carbon capture, circular bioeconomy integration, and multi product biorefinery models, large scale deployment remains constrained by cultivation, harvesting, and downstream processing costs [119]. Therefore, future competitiveness of marine microalgal energy systems will depend on technological advances in strain optimisation, process intensification, and integration with existing industrial carbon and wastewater management infrastructure.

3. Challenges and limitations

While sustainable energy solutions offer promising alternatives to fossil fuels, their widespread adoption is hindered by several challenges and limitations. These obstacles span across cultivation and harvesting difficulties, economic and technological barriers, as well as environmental and regulatory concerns. Addressing these issues is crucial for ensuring the long-term viability and scalability of renewable energy production [120].

3.1. Problems with cultivation and harvesting

One of the major challenges in sustainable energy production, particularly in biofuels and hydrogen generation, lies in the cultivation and harvesting of biological feedstocks. Large-scale cultivation of biomass, including microalgae, energy crops, and other organic sources, faces significant hurdles in terms of land use, water demand, and nutrient supply. Many biofuel feedstocks require vast amounts of arable land, which can compete with food production and lead to deforestation. Additionally, microalgae, often considered an efficient source of biofuels, require controlled environments for optimal growth. Achieving high biomass productivity demands precise nutrient balancing, temperature control, and exposure to sufficient light, making large-scale operations complex and costly. High lab yields have been obtained for microalgae, but translating them to outdoor productivity has been a challenge [121]. Sunlight energy is usually utilized at low efficiency in conversion to biomass through photosynthesis [122]. Contamination and sustenance of culture over a long period in outdoor open conditions has been a major challenge.

Harvesting and dewatering methods further complicate biofuel production due to their high energy requirements. In microalgal biofuel production, the process of separating algae from water is energy-intensive and inefficient when scaled up. Common harvesting methods such as centrifugation, membrane filtration, and chemical flocculation significantly increase operational costs and energy demand, often accounting for a substantial portion of total production costs. In addition, downstream processing challenges such as solvent based lipid extraction, cell disruption requirements, and biomass drying further increase process complexity and reduce overall energy return. Although emerging approaches such as wet biomass conversion and integrated biorefinery processing are being explored, achieving cost effective, large scale, continuous processing remains a major industrial challenge. These factors collectively contribute to the persistent gap between laboratory scale success and commercial scale deployment [123]. Additionally, scaling up these techniques increases operational costs, making the process less economically viable. As of now, the only viable harvesting methods for medium value products like biofuels are partial settling of select algae with self-aggregation features (eg.: *Dunaliella* species, *Phormidum* species, *Tetraselmis* species) and natural sedimentation of algae at the end of growth cycle upon depletion of nutrients [124]. These are possible only with select algae and select conditions. The search for low-energy and cost-effective harvesting methods remains an ongoing challenge that must be addressed for biofuel technologies to compete with fossil fuels on a commercial scale.

3.2. Bioreactor design, engineering trade offs and scalability

Bioreactor design presents additional engineering challenges that directly influence process scalability and economic feasibility [125]. Closed photobioreactors provide improved contamination control and higher productivity but require high capital investment and complex operational management [126]. In contrast, open raceway pond systems offer lower capital costs and easier scale up potential but are more vulnerable to environmental fluctuations, contamination, and lower biomass productivity. Engineering trade offs must also consider light penetration versus culture density, mixing energy requirements versus productivity gains, and gas transfer efficiency versus operational cost [127]. At large scale, maintaining uniform light exposure, temperature stability, and nutrient distribution becomes increasingly complex, particularly in marine cultivation environments. These scalability limitations highlight the need for hybrid cultivation strategies, improved reactor materials, and advanced monitoring systems to support economically viable industrial scale marine microalgal production.

3.3. Economic and technological obstacles

These interconnected processing and engineering constraints directly influence techno economic feasibility and lifecycle sustainability, highlighting the importance of integrated system level optimisation for future commercial scale marine microalgal bioprocesses. The high production cost associated with sustainable energy technologies remains a significant limitation. Biofuel production, hydrogen generation, and carbon capture technologies require sophisticated equipment, advanced processing techniques, and extensive infrastructure [128]. The capital investment needed for research, development, and deployment often makes renewable energy options more expensive than traditional fossil fuels. Enzymatic hydrogen production and photobiological hydrogen generation require specialized bioreactors, genetic modifications, and metabolic pathway optimisation, all of which add to the cost [129]. Similarly, the conversion of biomass into biofuels through biorefinery processes involves multiple stages, such as pre-treatment, lipid recovery, fermentation, and upgrading, each contributing to the overall expense [130].

Recovery of oil from algae is another key challenge. Unlike vegetable oil extraction (which involves extraction of oil from seed kernels), extraction of oil from microalgae involves extraction of oil from within algal cells which are encased by sturdy cell walls. This usually requires a pre-treatment step (wet milling, sonication, microwave treatment) for cell wall disruption. Also, the harvested algae is wet (60-80% water) unlike vegetable oil extraction where the seed kernels are dry. This means either a land/energy/equipment-intensive drying step is required or new wet algal processing methods have to be developed/scaled-up [121]. Hydrothermal liquefaction and polar solvent extraction preceding non-polar solvent extraction are such methods and they require development in scale-up [5,121].

Despite these economic barriers, advancements in biorefinery solutions offer potential pathways for cost reduction. Biorefineries integrate multiple processes, allowing for the simultaneous production of biofuels, biochemicals, and bio-based materials, thereby enhancing profitability. The concept of the “Best Available Solutions in Biorefinery” focuses on optimizing efficiency and yield through the use of advanced catalysts, co-product recovery, and process integration. Biogas, animal feed and bioplastics from deoiled algae and a variety of chemicals through hydrothermal liquefaction route are some of the value-addition coproducts that can be developed through a biorefinery approach [5,121,131]. By refining waste streams into valuable byproducts, biorefineries can improve the economic feasibility of sustainable energy production. However, the challenge remains in scaling up these technologies while ensuring consistent feedstock supply and minimizing processing costs.

Another key technological obstacle is the efficiency of energy conversion. Many sustainable energy solutions, such as hydrogen production through biological pathways or carbon capture utilization, suffer from low conversion rates. Improving the efficiency of microbial metabolic processes, enzymatic reactions, and catalytic transformations requires continuous innovation and investment in biotechnology and engineering. Without significant improvements in yield and process efficiency, these technologies may struggle to compete with conventional energy sources.

Technoeconomic analysis of integrated biofuel production with value-addition coproducts in the form of a biorefinery indicates the production scale may be required at a magnitude of 100 ha [32,121]. Year-round sustained average productivity in the range of 20-25 g/m^2/day. Value-addition from coproducts has been found to be the next most influential factor in the production factor after scale and biomass productivity. Lipid content and lipid extraction efficiency follow those. Lipid content shall be about 20% and extraction efficiency shall be above 90%. Presently, algal biofuel production cost before value-addition is estimated to be about $ 3.50/L. Value-addition input credits from deoiled algae as aquafeed brings down the price to $ 1/L. Capital cost contribution to the overall fuel production cost is high, more than 50%. This is an indication of high capital costs. Looking at step-wise cost breakdown, the algal growth step itself excluding the harvest step, makes up for 70% of the total fuel production cost.

To summarise the major barriers to large scale commercial deployment, key limiting factors and associated research priorities are outlined in Table 3.

3.4. Environmental and regulatory concerns

The environmental impact of large-scale biomass cultivation raises concerns regarding sustainability. Expanding biofuel production can lead to unintended ecological consequences, such as deforestation, water depletion, and biodiversity loss. The cultivation of energy crops, including corn, sugarcane, and palm oil, has been linked to habitat destruction and increased greenhouse gas emissions due to land-use changes [133]. Similarly, microalgae cultivation at large scale can cause nutrient imbalances in aquatic ecosystems, potentially leading to harmful algal blooms by residual nutrients discharged back to sea with the return of spent sea water. Managing these environmental risks is critical to ensuring that biofuel and biomass-based energy solutions do not inadvertently contribute to ecological degradation [134]. The relative upside to microalgae cultivation are: marine algae can be used meaning sea water can be used as water source instead of freshwater; non-arable land can be used meaning marginal or waste lands can be used instead of agriculture/fertile land; wastewater can also be used as water source; it can be combined with industrial wastewater remediation [5]. When sea water is used as water source and it is discharged back to sea after being used as algal growth medium for a while, any left-over concentration of nutrients such as nitrogen and phosphorus should be below the discharge limits [135].

Regulatory and policy challenges also hinder the commercialization of sustainable energy technologies. Governments play a crucial role in shaping the energy landscape through subsidies, tax incentives, and carbon pricing mechanisms [136]. However, inconsistent regulatory frameworks across different regions create uncertainty for investors and industry stakeholders. Stringent policies regarding land use, water consumption, and waste disposal further complicate the deployment of biofuel and hydrogen technologies. Additionally, the approval process for novel bio-based energy solutions often involves extensive safety assessments and compliance with environmental regulations, delaying market entry [137].

To overcome these regulatory barriers, policymakers must develop clear and supportive guidelines that facilitate the transition to renewable energy. International collaboration is also necessary to establish standardized sustainability criteria for biofuel production, carbon capture utilization, and other green technologies. Incentivizing research and development through grants and funding opportunities can further accelerate technological advancements and reduce economic risks for businesses investing in sustainable energy solutions [138]. Despite their potential to mitigate climate change and reduce reliance on fossil fuels, sustainable energy technologies face significant challenges related to cultivation, harvesting, economic feasibility, technological efficiency, and regulatory constraints. Addressing these limitations requires a multi-faceted approach, including advancements in biotechnology, process optimisation, cost reduction strategies, and supportive policy frameworks. By overcoming these obstacles, sustainable energy solutions can become more competitive, scalable, and environmentally responsible, paving the way for a cleaner and more resilient energy future [139].

Table 3
Techno-economic challenges in sustainable energy.

Limiting Factor Category	Core Challenge	Impact on Commercialization	Linked Research Priority	Reference
Cultivation and Productivity	Sub optimal biomass productivity under variable environmental conditions, strain instability, and contamination risk	Reduces overall fuel yield and increases production cost per unit biomass	Development of high productivity marine strains, stress tolerant strains, and adaptive cultivation strategies	[132]
Harvesting and Downstream Processing	High energy demand for biomass recovery, dewatering, drying, and solvent extraction	Major contributor to operational cost and negative energy balance	Low energy harvesting technologies, wet biomass processing, integrated biorefinery conversion systems	[121]
Reactor Design and Scalability	High capital cost of closed systems, contamination risk in open systems, light penetration and mixing limitations at scale	Limits large scale deployment and industrial feasibility	Hybrid cultivation systems, improved photobioreactor design, advanced monitoring and process automation	[121]
Techno Economic Feasibility	High capital and operational costs, infrastructure requirements, supply chain limitations	Delays commercial adoption and market competitiveness	Integration with carbon capture, wastewater treatment, and multi product value chain development	[121]

4. Emerging technologies and future applications

The future of sustainable energy lies in the continuous evolution of advanced technologies and innovative applications. Emerging fields such as genetic engineering, bioreactor optimisation, circular bioeconomy integration, and industrial collaborations are driving significant progress in biofuel production, hydrogen generation, and biomass recovery [140]. These advancements aim to enhance energy efficiency, reduce costs, and make sustainable energy solutions more commercially viable. By leveraging cutting-edge biotechnology, automation, and policy support, the transition to a more resilient and sustainable energy system is becoming increasingly achievable.

4.1. Genetic engineering and strain improvement

Genetic engineering has revolutionized the field of biofuel production by enabling the modification of microorganisms and algae for higher productivity and resilience. Techniques such as CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats) and synthetic biology allow precise genetic modifications to enhance the metabolic pathways of biofuel-producing strains. Through CRISPR-based gene editing, scientists can selectively knock out genes responsible for energy loss and insert genes that boost lipid accumulation, essential for biodiesel production. Synthetic biology further enables the design of artificial metabolic circuits, optimizing microbial strains for efficient bioethanol and biogas production [141].

While CRISPR based genome editing and synthetic biology approaches offer significant opportunities for enhancing marine microalgal productivity and metabolic efficiency, several biological, regulatory, and ecological constraints must be considered [142]. Biological limitations such as metabolic burden, reduced growth stability under industrial conditions, and unintended pathway interactions may reduce long term strain performance [142]. In addition, regulatory approval pathways for genetically modified microalgae remain complex and vary significantly across regions, particularly for open environment or large scale outdoor cultivation systems. Ecological concerns related to accidental release, horizontal gene transfer, and potential impacts on native marine microbial communities also require careful risk assessment and monitoring [143]. In the near term, realistic advances are expected in strain optimisation for controlled cultivation systems and targeted metabolic pathway enhancement. In contrast, large scale environmental deployment of fully engineered synthetic microalgal systems is likely to remain a longer term objective requiring further regulatory and ecological validation [144].

One of the primary goals of genetic engineering in biofuel applications is increasing lipid productivity and stress tolerance. Microalgae and bacteria engineered for higher lipid accumulation produce greater biofuel yields with lower resource inputs. Additionally, introducing stress-resistant traits enables these microorganisms to thrive in extreme conditions, such as high salinity, temperature fluctuations, and limited nutrient availability [145]. These improvements contribute to the scalability of biofuel production by ensuring consistent and high-yield performance under industrial conditions. As research in genetic engineering advances, future applications may include engineered microbes capable of directly converting atmospheric carbon dioxide into high-energy biofuels, further integrating carbon sequestration with renewable energy production [140].

Although synthetic biology and CRISPR based tools offer transformative potential for marine microalgal biotechnology, their long term success will depend on responsible innovation supported by advances in biological robustness, regulatory frameworks, and environmentally safe large scale deployment strategies.

4.2. Bioreactors and cultivation system advances

Optimizing cultivation systems is crucial for scaling up biofuel production while minimizing resource consumption. Advances in bioreactors and farming techniques are paving the way for more efficient and automated biomass cultivation. Photobioreactors and open pond systems represent two primary approaches to large-scale microalgae cultivation, each with unique advantages and challenges [146].

Photobioreactors are enclosed systems that provide optimal conditions for microalgae growth by regulating light exposure, carbon dioxide supply, and nutrient availability. These reactors enhance biomass productivity by preventing contamination and maintaining ideal growth environments. While traditionally costly, recent innovations in material science and automation have significantly reduced the operational costs of photobioreactors, making them more viable for industrial-scale algal production. Presently, the photobioreactors are deemed to be a viable option for high-value products such as food supplements and nutraceuticals and are considered to be not yet viable for medium-value products such as biofuels [147]. Tubular photobioreactors are the most extensively used photobioreactors and the tubes can be arranged either horizontally or stacked up vertically (Fig. 4). Vertical flat plate photobioreactors are another prominent form of photobioreactors (Fig. 5) [121].

Open pond systems, on the other hand, offer a low-cost alternative for large-scale microalgae cultivation. These systems utilize natural or artificial ponds to grow biomass under sunlight, reducing energy inputs. Raceway ponds are a prominent type of open pond system that are used for algal cultivation. Raceway ponds include a paddlewheel powered by a motor that circulates the algal culture along channels for mixing (Figs. 6 and 7). With open systems, challenges such as contamination, water evaporation, and uneven light distribution must be addressed to improve efficiency. Hybrid systems that integrate the benefits of both photobioreactors and open ponds are emerging as a promising solution for balancing cost and productivity. Fig. 4 shows an open system developed based on sunlight-distribution for improved yield, given that outdoor sunlight is typically 4-5 times the saturation light intensities of algae [121]. Local algal strains and local consortia of multiple algal

Fig. 4. A horizontal tubular algal photobioeactor set up at the Wageningen University, Netherlands (vertical tubular photobioreactor at top left) [148].

Fig. 5. A vertical flat plate photobioreactor set up at the Arizona Center for Algae Technology and Innovation, Arizona State University, USA (energy.gov).

Fig. 6. A large-scale algal raceway pond (1.25 ha) in Christchurch, New Zealand [149].

strains and/or bacteria are likely to be the most viable options for open outdoor cultivation [5]. These strains may be better overall than other non-native algal strains because they may sustain much better in open outdoor conditions even if their growth rate and lipid content may be lower and this would result in better long-term productivity in the form

Fig. 7. Sunlight distribution-based open algal growth system (220 sq. m/ 100,000 L) with a raceway pond inoculum system (6000 L) at The Energy and Resources Institute, Navi Mumbai, India [121].

of annual yield.

Another transformative innovation in cultivation is hands-free farming practices, where automation and artificial intelligence (AI) optimize yield with minimal human intervention. AI-powered monitoring systems analyze real-time data on nutrient levels, light exposure, and biomass growth, automatically adjusting conditions to maximize productivity. These advancements reduce labor costs, improve consistency, and enhance scalability, making sustainable energy production more feasible at a global level. Developments are being made to monitor the health and the potential impending contamination of the algal culture through real-time online sensors and response mechanisms [150].

Relating to harvest of algae as part of the cultivation system, natural sedimentation of alga upon nutrient depletion at the end of the growth cycle and partial settling of select algae that have self-aggregating features (Fig. 8) are the two viable harvest methods employed currently. Some of the other algal harvest approaches that hold potential are use of bioflocculation microbes (including cyanobacteria) as co-cultures, employing biopolymers with local surface charges for flocculation of algae and used of other bio-based flocculants.

4.3. Integration with the circular bioeconomy

The integration of biofuel production with the circular bioeconomy is essential for long-term sustainability. A circular bioeconomy promotes the efficient use of biological resources, minimizing waste and maximizing value across multiple industries. Microalgae synergies with renewable energy fit well into this framework by linking carbon capture, waste utilization, valorization of the whole biomass, and biofuel generation [107].

Microalgae cultivation can be coupled with industrial carbon capture systems, where emissions from power plants and factories serve as a carbon source for algae growth. This approach not only reduces greenhouse gas emissions but also converts waste CO_2 into valuable biofuels and bioproducts. Additionally, wastewater treatment facilities can integrate microalgae-based systems to simultaneously remove contaminants and produce biomass for biofuel applications [151].

The adoption of multi-product approaches to sustainability further strengthens the economic viability of biofuel production. Instead of focusing solely on fuel generation, biorefineries are increasingly developing value-added co-products such as biofertilizers, bioplastics, pharmaceuticals, and animal feed. This diversified approach enhances revenue streams, mitigates financial risks, and promotes a more resilient bio-based economy. By aligning biofuel production with circular bioeconomy principles, industries can create closed-loop systems that maximize resource efficiency and minimize environmental impact.

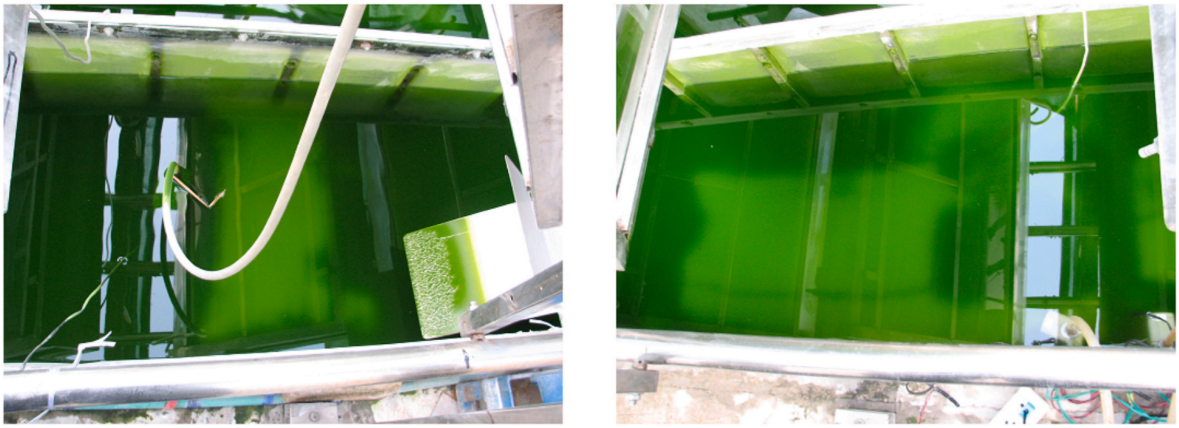

Fig. 8. Harvesting of algae by partial settling of select algae with self-aggregation features and subsequent sweeping and collection [121].

Biogas and biofertilizers can be developed by anaerobic digestion of deoiled algae with the carbon dioxide by-product in turn captured and utilized for enhanced algal production [131]. Platform/intermediate chemicals such as organic acids, alkanes, alkenes, ammonia, amines, amides, benzene and other monoaromatics, aldehydes, furfural derivatives, ketones, polycyclic compounds and nutrients can developed through hydrothermal liquefaction of algae for biofuels and a variety of coproducts in a biorefinery approach [121]. Polyurethane is being developed as a bioplastic from algae [5]. A representative integrated production in the form of biorefinery referenced above by Kannan et al. (2025) is shown in Fig. 9 [121]. As of now, the most promising coproduct valorization option seems to be aquafeed and animal feed from deoiled algae and glycerol as platform chemical, following solvent extraction of lipids. The work by Kannan et al. (2025) shows that biofuels can be produced from algal biomass at USD 3.40/L before any value addition from coproducts [121]. This cost is estimated for realistically achievable culture growth and processing conditions such as 130 ha scale; 25 g/m2/day biomass productivity; 20% lipid content; 95% wet algal lipid extraction efficiency. This means the rest 80% of the algae is deoiled algae and about 10% of lipid-equivalent mass as glycerol by-product from transesterification. Now, the deoiled algal biomass can be sold at USD 0.60/kg as aquafeed source [5]. Crude glycerol can be sold at USD 0.16/kg for use as industrial platform chemical. This brings down the net cost of production of algal biofuel to USD 1.02/L from USD 3.40/L. This is a much more viable scenario economically and is competitive with the current fuel prices [121]. However, this set of coproduct selection may change in future if hydrothermal liquefaction route become more cost-competitive. In that case, aforementioned coproducts related to hydrothermal liquefaction method would come to the fore.

4.4. Industry trends and the commercialization process

The biofuel and bioenergy markets are experiencing rapid growth due to increasing global demand for clean energy solutions. Governments, industries, and research institutions are investing heavily in

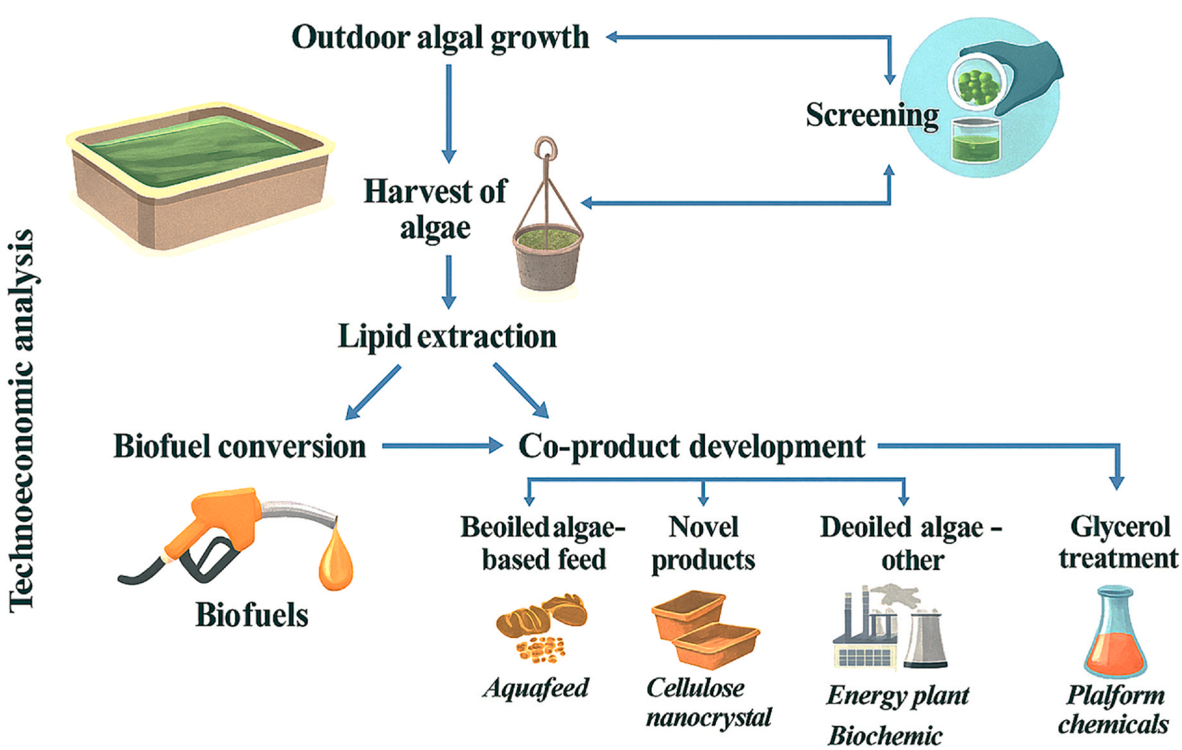

Fig. 9. Schematic of integrated production of algal biofuels and bioproducts in the form biorefinery.

developing sustainable alternatives to fossil fuels. The expansion of the biofuel sector is driven by technological advancements, favourable policies, and the rising adoption of renewable energy targets by various countries [152].

Collaborations among industries and policy initiatives play a critical role in accelerating the commercialization of biofuels and other sustainable energy technologies. Public-private partnerships facilitate knowledge exchange, infrastructure development, and financial support for large-scale projects. Government policies, including carbon pricing, renewable energy incentives, and subsidies for biofuel producers, provide a supportive framework for market expansion. International collaborations further enhance technology transfer, allowing developing nations to adopt sustainable energy solutions more efficiently [153].

The emergence of advanced technologies in genetic engineering, bioreactor optimisation, circular bioeconomy integration, and industrial collaborations is reshaping the future of sustainable energy. By enhancing strain productivity, improving cultivation efficiency, and leveraging automation, the scalability of biofuel production is steadily increasing. The integration of biofuel systems with broader sustainability initiatives ensures a holistic approach to energy transition. While challenges remain in commercialization and market penetration, continuous innovation and supportive policies will drive the widespread adoption of sustainable energy technologies. The future of renewable energy is deeply interconnected with interdisciplinary advancements, paving the way for a cleaner, greener, and more resilient global energy landscape [120].

To provide a critical assessment of technology readiness and deployment potential, emerging marine microalgal technologies are categorised according to development maturity as summarised in Table 4.

Based on current technological maturity and industrial translation potential, the following research directions are expected to deliver the most significant impact in marine microalgal biotechnology over the next decade.

4.4.1. High productivity marine strain optimisation

Development of marine microalgal strains with enhanced lipid accumulation, faster growth kinetics, and improved tolerance to salinity and temperature fluctuations using CRISPR based and adaptive evolution approaches.

4.4.2. Low energy harvesting and wet biomass processing

Development of energy efficient harvesting methods such as bioflocculation, magnetic separation, and membrane assisted recovery combined with wet biomass conversion technologies.

4.4.3. Hybrid cultivation system design

Optimisation of combined open pond and closed photobioreactor systems to balance productivity, contamination control, and capital cost.

4.4.4. Industrial integration with carbon capture and wastewater systems

Coupling marine microalgal cultivation with industrial flue gas CO2 capture and marine or coastal wastewater nutrient removal systems.

4.4.5. Marine microalgal biorefinery development

Development of integrated multi product processing systems generating fuels, omega fatty acids, pigments, and biomaterials from single biomass streams.

5. Conclusion

Marine microalgae represent a highly promising platform for sustainable energy production, carbon capture, and circular bioeconomy integration; however, several critical bottlenecks continue to limit large scale commercial deployment. Key constraints include variability in large scale cultivation productivity, high energy requirements associated with harvesting, dewatering, and downstream processing, and engineering challenges related to reactor design and process scalability. Addressing these limitations will require targeted research and coordinated investment in priority areas including high productivity strain development, low energy biomass recovery technologies, hybrid cultivation system optimisation, and integration of microalgal systems with industrial carbon capture and wastewater treatment infrastructure. In the near term, achievable gains are expected through process optimisation, improved cultivation control, and enhanced biomass conversion efficiency within controlled production environments. In contrast, longer term advancements are likely to include fully integrated marine biorefinery platforms, advanced synthetic biology driven strain engineering, and large scale deployment of climate integrated microalgal production systems. Continued progress across these priority areas will be essential to transition marine microalgal biotechnology from research driven innovation to commercially viable and environmentally sustainable industrial implementation.

Current evidence indicates that marine microalgae are transitioning from being primarily studied as ecological primary producers to becoming central components of next generation sustainable bioresource platforms. Their unique combination of high photosynthetic efficiency, rapid biomass productivity, carbon capture capability, and biochemical versatility positions them at the intersection of climate mitigation, renewable energy production, and circular bioeconomy development. Recent advances in strain engineering, bioreactor optimisation, and integrated biorefinery concepts further strengthen the feasibility of large scale deployment. Importantly, the coupling of

Table 4
Technology maturity framework for emerging marine microalgal technologies.

Technology Area	Laboratory Scale Proof of Concept	Pilot Scale Validation	Commercial Deployment Status	Key Constraints and Trade Offs	Reference
Genetic Engineering and Synthetic Biology	Demonstrated pathway modification, lipid enhancement, stress tolerance engineering	Limited pilot testing in controlled cultivation systems	Not widely deployed commercially	Strain stability, regulatory approval, biosafety concerns, ecological risk	[141, 142]
AI Driven Cultivation Optimisation	Demonstrated predictive modelling and cultivation control in experimental systems	Early pilot implementation in automated cultivation platforms	Limited commercial adoption	Data quality requirements, system integration complexity, high initial investment	[154]
Advanced Photobioreactor Systems	High productivity demonstrated under controlled conditions	Pilot scale deployment in hybrid cultivation facilities	Limited large scale commercial deployment	High capital cost, energy consumption, scalability limitations	[121]
Circular Bioeconomy and Integrated Biorefineries	Demonstrated multi product recovery at laboratory scale	Pilot scale multi product demonstration facilities emerging	Early stage commercial integration in niche sectors	Supply chain complexity, product market variability, process integration challenges	[107] [151] [131]
Thermochemical Conversion Technologies (HTL, Pyrolysis)	Demonstrated fuel production from wet biomass at laboratory scale	Pilot scale reactor demonstration in several regions	Early commercial demonstration projects emerging	Reactor cost, energy input requirements, feedstock variability	[155]

microalgal systems with industrial carbon capture, wastewater remediation, and multi product bioprocessing frameworks provides a realistic pathway toward improving economic viability. As global energy and environmental pressures intensify, marine microalgae based technologies are expected to play an increasingly important role in supporting carbon neutral fuel production, sustainable chemical manufacturing, and integrated environmental management systems.

Future research should focus on optimizing strain selection and outdoor sustenance, viable harvest methods, improving extraction methodologies, and developing innovative biorefinery approaches to maximize the utility of microalgal biomass. Policy support, investment in research and development, and interdisciplinary collaboration are crucial to overcoming existing limitations and unlocking the full potential of marine microalgae. With continued advancements in biotechnology and sustainable cultivation practices, marine microalgae could emerge as a cornerstone of renewable energy, environmental conservation, and biopharmaceutical industries. Their contribution to global sustainability efforts underscores the need for further exploration and development, ensuring a cleaner, greener future driven by nature's microscopic powerhouses.

CRediT authorship contribution statement

Yuvaraj Dinakarkumar: Writing – review & editing, Conceptualization. **Dheeban Chakravarthi Kannan:** Writing – review & editing, Conceptualization. **Panneerselvam Theivendren:** Writing – original draft, Conceptualization.

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