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Microalgae: Promising solutions paving the way toward a greener and more sustainable future

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Microalgae represent a promising solution for achieving greener and more sustainable applications, owing to their rapid growth rates, high photosynthetic efficiency, and capacity to produce valuable compounds such as lipids. Biofuels based on microalgae have emerged as a promising alternative to fossil fuels due to their sustainable and renewable nature. Moreover, the use of microalgae cultivated in wastewater not only contributes to biofuel production but also provides additional benefits such as wastewater treatment and CO_2 sequestration to realize the carbon neutrality. However, the commercial viability of microalgae-based biofuels remains uncertain. This article reviews advancements in microalgae-based sustainable production while exploring its multi-objective applications beyond energy generation. Multi-objective applications, including multi-algal systems, species development, process optimization, and dust suppressant are necessary to improve cost-effectiveness and enhance overall feasibility.

KEYWORDS

microalgae, biofuel, renewable, multi-objective applications, by-products

1 Introduction

Microalgae have emerged as a promising solution for advancing greener and more sustainable applications across various industries. Renewable energy based on microalgae represents one of the most significant applications. The utilization of fossil fuels releases greenhouse gases (GHGs), significantly impacting the global climate and threatening both human life and ecological systems. Currently, fossil fuels meet a substantial portion of global energy demand, leading to critical challenges such as energy crises and environmental degradation. To address these issues, there is a need to explore sustainable, renewable, and efficient energy sources (Abdullah et al., 2024). Biofuels derived from microalgae show great potential as a viable and sustainable alternative energy source, while also reducing adverse environmental impacts. They represent a promising candidate for achieving green development, not only in biofuel production but also in various other eco-friendly applications.

Microalgae encompass a diverse group of microorganisms, including green algae, red algae, brown algae, diatoms, and blue-green algae (cyanobacteria), among others (Jalilian et al., 2020). Microalgal cells can obtain energy heterotrophically by assimilating organic carbon from growth media, either through chemo-heterotrophy or photoheterotrophy using light to enhance carbon assimilation (Nair and Chakraborty, 2020). Specific strains exhibit diverse applications. Microalgae represent a promising energy source due to their

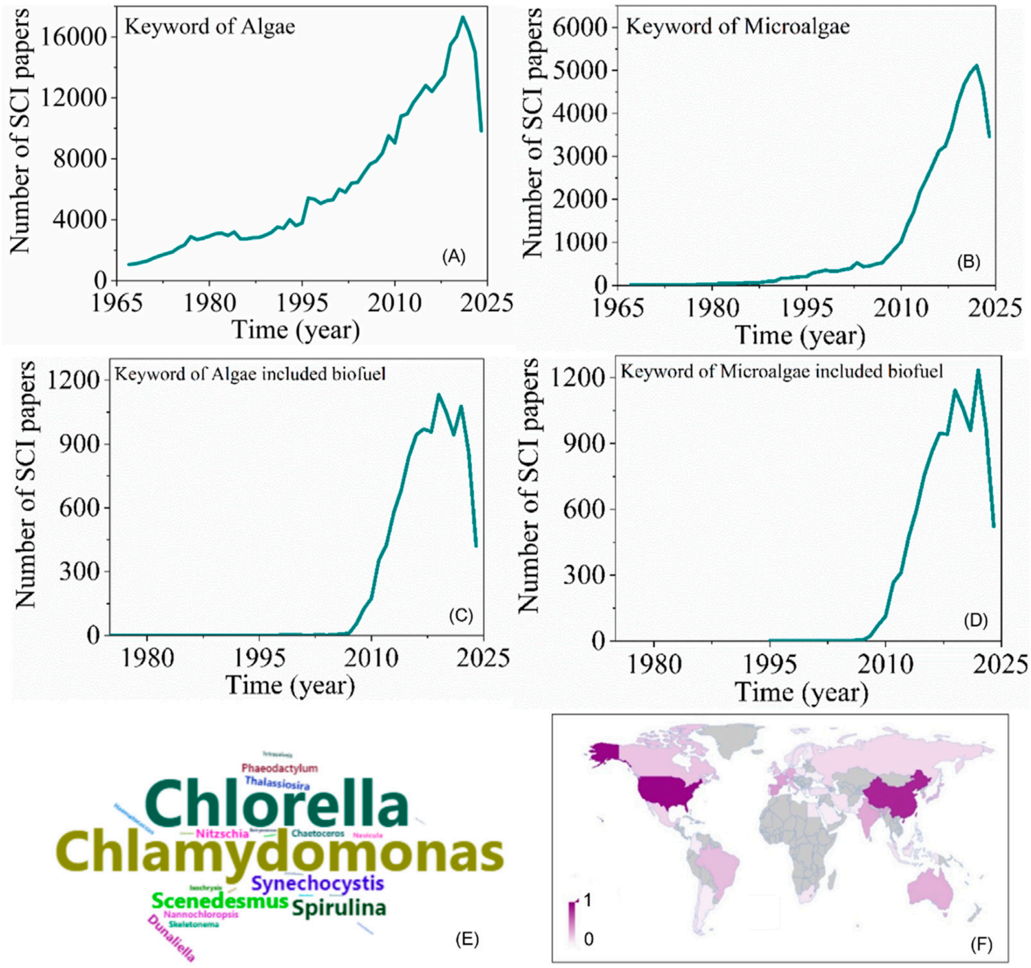

FIGURE 1
The status of biofuel based on algae. **(A)** displayed the number variation of articles based on key word of algae. **(B)** displayed the number variation of articles based on key word of microalgae. **(C)** displayed the number variation of articles based on key word of algae included biofuel. **(D)** displayed the number variation of articles based on key word of microalgae included biofuel. **(E)** displayed the word cloud based on topic of microalgal strains. **(F)** displayed the map based on research about microalgal biofuel.

minimal water requirements, high biomass yield per unit area compared to traditional crops, ability to utilize non-arable land, and capacity to recycle agro-industrial waste as nutrients (e.g., animal breeding effluents or vinasse). Furthermore, their ability to synthesize lipids has positioned them as a key focus for biodiesel production and other high-value products (Menegazzo and Fonseca, 2019).

Microalgal biofuel has attracted significant attention in recent years; however, several challenges remain that impede further development. Researchers have been seeking solutions. The first large-scale cultivation of microalgae began in the early 1960s in Japan using *Chlorella*, focusing on its culture (Spolaore et al., 2006). Interest in microalgae for renewable energy grew during the 1970s oil crisis (Mata et al., 2010). In response, the U.S. National Renewable Energy Laboratory (NREL) launched the Aquatic Species Program (ASP) from 1978 to 1996, exploring alternative renewable fuels, including microalgae-derived biodiesel (Mata et al., 2010). Algal biofuel research became a prominent focus in renewable energy studies during the new millennium, particularly between 2007 and 2017. This period saw a three-stage progression: initial growth, exponential expansion, and eventual decline due to field saturation. Since 2010, however, there has been notable progress in algal biotechnology and bioproducts driven by biofuel applications (Chen et al., 2019).

Unfortunately, the current production of microalgal biofuels remains less competitive compared to fossil fuels due to high costs (Deconinck et al., 2018). Efforts are being made to optimize algae utilization through multi-objective approaches. Moreover, emerging technologies like artificial intelligence show significant potential for optimizing parameters in microalgae production. This review aims to provide a comprehensive overview of biofuel and multi-objective applications in microalgae research.

2 Method and material

The data presented in the figures were retrieved from the Web of Science database. The search terms used included "algae", "microalgae", "algae and biofuel", and "microalgae and biofuel". The map illustrates the number of research publications by country related to the keyword 'microalgal biofuel', with a standardized score ranging from 0 to one based on the number of articles. Data visualization was conducted using Origin 2024b and R Studio software.

3 Multi-objective applications

3.1 The status of biofuel based on microalgae

As shown in Figure 1, research on microalgal strains has surged in recent years, with notable focus on *Chlorella*, *Spirulina*, *Scenedesmus*, *Chlamydomonas*, and *Synechocystis*. Among these, *C. vulgaris* (*Chlorella vulgaris*) is a widely studied green microalga belonging to the genus *Chlorella* and cultivated in freshwater (Okoro et al., 2019). *C. vulgaris* features an enzyme-digestible cell wall, spherical microscopic cells ranging from 2 to 10 μm in diameter, and a cell wall thickness that increases during growth, reaching 17–21 nm by maturity (Okoro et al., 2019). Its ability to accumulate lipids makes it highly suitable for biodiesel production. The rigidity of *C. vulgaris* cells arises from a thin unilaminar layer that thickens as the cell matures, forming a microfibrillar structure composed of glucosamine monosaccharide layers. Reproduction occurs asexually; under optimal conditions, a mother cell can divide into four daughter cells upon rupturing at maturity. The remnants of the mother cell provide nourishment for the rapidly growing daughter cells (Okoro et al., 2019). Microalgae hold great promise as a renewable source for sustainable biodiesel production due to their capacity to accumulate high lipid content (20%–75% by weight) (El Shimi and Moustafa, 2018).

Achieving breakthroughs in biomass accumulation and lipid production are two pivotal factors for realizing microalgal biofuel. The first step involves selecting promising microalgal strains through a systematic process. In recent years, many researchers have focused on identifying potential candidates with specific objectives, often starting with the isolation of microalgae species. Several suitable candidates for biofuel production have been identified, including *Chlorella*, *Scenedesmus*, and others. Notably, these species are widely distributed in aquatic environments, indicating their superior stress tolerance capabilities. Furthermore, certain genera that have received less attention also possess advantageous traits for biofuel production. For instance, *Golenkinia* has garnered attention in recent years. Nie et al. (2018) investigated its capacity for degrading campus wastewater, demonstrating not only its high lipid content but also its ease of harvesting through gravity separation (Nie et al., 2018). Subsequently, they conducted extensive research on biomass and biofuel production (Nie et al., 2020a; Nie et al., 2020b). Rearte et al. (2024) assessed both the fatty acid composition and high-value by-products of caeronid (Rearte et al., 2024). Recent studies have highlighted the emergence of microalgal isolation in extreme environments. For example, one study focused on collecting airborne strains and found that these microalgae exhibited greater stress tolerance due to exposure to stringent environmental conditions, such as high illumination (Kumari and Singh, 2021). Therefore, the selection of promising microalgal strains with abundant lipid content, high biomass output, strong resistance to harsh environments, and ease of harvesting is a cornerstone.

3.2 Improvements for biodiesel quality and other types of bioenergy

Some nanomaterials have been used to improve biodiesel quality. For instance, Gad et al. (2021) recommended adding graphene nano sheet additives at a concentration of 100 ppm to biodiesel blends, as this significantly enhanced combustion characteristics, performance, and emissions reduction compared to standard biodiesel blends (Gad et al., 2021). Moreover, the pursuit of alternative types of biofuel development is highly advantageous. For instance, harnessing microalgae for biogas production presents a viable alternative for renewable energy due to the promising potential of algal carbohydrates as a source (Zabed et al., 2020). Some microalgae, including *Chlorella*, *Spirulina*, and *Scenedesmus*, are considered suitable biomass for biogas production (Ashour et al., 2024). Thus, leveraging diverse energy sources can effectively promote the utilization of microalgal energy.

3.3 The improvement for microalgal output

At the global scale, China and the U.S. have become key contributors to algal biofuel research. In the past, many studies focused on optimizing culture parameters to enhance biomass and lipid production. The growth rate of *C. vulgaris* was investigated in a photobioreactor (PBR). Results showed that the optimal biomass yield was achieved under specific conditions: pH 9–10, aeration flow rate of 200 L/min, illumination intensity of 5–7 klux, glucose and nitrate concentrations of 20 g/L and 0.5 g/L respectively, and temperature of 30°C. Notably, the biomass yield reached 3.43 g/L with a lipid productivity of 66.25 mg/L/d (S. Daliry et al., 2017). Furthermore, recent advancements such as omics-based analyses have deepened the understanding of molecular-level responses to specific environmental conditions. These findings not only provide insights into cellular mechanisms but also help identify compounds with enhanced potential for specific applications.

Several advanced methods have been employed. For example, recombinant CRISPR-Cas9 technology has successfully enhanced the total lipid content of microalgae, a crucial prerequisite for efficient biofuel production (Lakhawat et al., 2022). Additionally, various cultivation modes are currently under development. Jin et al. (2021) developed an efficient and scalable heterotrophic cultivation technology for the production strain *Chlorella sorokiniana* GT-1. By optimizing culturing conditions, ultrahigh biomass concentrations of 271 g/L were achieved in a 7.5 L bench-scale fermenter and 247 g/L in a 1,000 L pilot-scale fermenter (Jin et al., 2021). Integrating effectively specific microalgal cultivation methods into the production assembly line can fully unlock the potential for high microalgal yields.

3.4 Microalgal valuable by-products

Microalgae have diverse applications beyond biofuel production. They contain a rich array of bioactive compounds, such as carbohydrates, proteins, fatty acids, and others, making them suitable for supporting human and animal growth. Consequently, microalgal cultivation holds promise in food production systems, providing key bioactive compounds for pharmaceuticals and valuable ingredients for cosmetics. For instance, combining high light intensity with appropriate UV-A radiation under salinity stress resulted in the highest carotenoid content (2.75 mg/g dry weight), primarily composed of lutein and beta-carotene, as well as the highest lipid accumulation (35.3% DW) with elevated levels of polyunsaturated fatty acids, including alpha-linolenic acid (C18:3) and linoleic acid (C18:2) (Rearte et al., 2024). Furthermore, the biochemical composition, fatty acid profile, and *in vitro* digestibility of twelve microalgal biomasses were investigated to explore their potential for producing novel functional foods. Cyanobacteria (particularly *A. platensis F&M-C256*), *C. sorokiniana F&M-M49*, and *C. vulgaris Allma* exhibited higher crude protein contents and *in vitro* digestibility. Marine species had lower digestibility but contained elevated levels of polyunsaturated fatty acids (mainly eicosapentaenoic acid and docosahexaenoic acid) and significant amounts of palmitoleic, oleic, and palmitic acids. Freshwater algae displayed high concentrations of α-linolenic acid along with even greater quantities of palmitic acid (Niccolai et al., 2019).

Moreover, *Arthrospira* and *Chlorella* are utilized in skincare product production. Microalgal extracts find extensive application in face, skin, hair care, and sun protection products. Microalgal components are commonly used in cosmetic products as antioxidants, thickening agents, and water-binding agents. Several commercial products have been developed with specific properties claimed by their manufacturers. For example, *Arthrospira* produces a protein-rich extract functioning as an anti-aging agent (Protulines, Exsymol S.A.M., Monaco). Similarly, the extract of *C. vulgaris* stimulates collagen production in the skin, leading to tissue regeneration and reduction of wrinkle formation (Dermochlorella, Codif, St. Malo, France). Recently launched by Pentapharm (Basel, Switzerland), Pepha-Tight incorporates *Nannochloropsis oculata*, known for its exceptional skin tightening properties. Another product, Pepha-Ctive, utilizes an extract from *D. salina*, which significantly promotes cell growth and enhances skin energy metabolism (Rizwan et al., 2018). To date, in the context of the food industry, algal protein, DHA, and pigments have been widely accepted by many consumers. Additionally, various skincare products also require significant amounts of algal components. This trend is promising, and both food and cosmetic products must ensure safety throughout the production process.

3.5 Wastewater act as the medium for microalgae growth

Researchers have introduced microalgae into wastewater treatment systems due to their ability to efficiently uptake nitrogen, phosphorus, and organic compounds for autotrophic growth (Jiang et al., 2021). These nutrients are typically present in high concentrations in wastewater. Furthermore, using microalgae as a feedstock for wastewater treatment reduces cultivation costs compared to artificial media. Microalgae have demonstrated promising potential in the bioremediation of emerging contaminants (ECs) due to their capacity to uptake and metabolize a wide range of organic pollutants. They can convert complex organic compounds into simpler, less toxic forms through diverse metabolic pathways. Moreover, employing microalgae for EC removal represents an environmentally friendly approach that can be seamlessly integrated with biofuel production, offering a sustainable and economically viable solution. ECs include a wide range of synthetic or naturally occurring chemicals and microorganisms that are not routinely monitored in the environment but possess the potential to infiltrate ecosystems and induce recognized or suspected adverse effects on both ecological systems and human health. These substances encompass pharmaceuticals and personal care products (PPCPs), endocrine-disrupting chemicals (EDCs), nanoparticles, flame retardants, and various industrial chemicals (Ethiraj and Samuel, 2024).

With the advancement of technology, artificial intelligence (AI) and big data have emerged as valuable tools for optimizing microalgal cultivation parameters to achieve maximum productivity. AI enables the rapid determination and adjustment of precise operational parameters, thereby significantly enhancing both microalgal cultivation efficiency and wastewater treatment performance. For instance, decision tree models were employed to analyze datasets of Trebouxiophyceae and Chlorophyceae classes for wastewater treatment optimization. The models identified nine parameter combinations for high biomass production, eleven combinations each for achieving high nitrogen removal efficiency and high phosphorus removal efficiency specifically for the Trebouxiophyceae class. Similarly, eleven combinations were detected for maximizing biomass production, nine for enhancing nitrogen removal efficiency, and eight for improving phosphorus removal efficiency within the Chlorophyceae class (Singh and Mishra, 2022).

Microalgae exhibit significant potential for the efficient treatment of municipal, agricultural, and industrial wastewater. However, substantial challenges remain in transitioning microalgal wastewater treatment technologies from laboratory settings to real-world applications. In particular, the removal of emerging contaminants remains a critical challenge in practical wastewater treatment scenarios. Therefore, novel approaches or strategies should be developed, and their underlying mechanisms should be systematically investigated using omics data, engineering principles, and artificial intelligence tools.

3.6 Microalgae play a significant role in promoting eco-friendly processes

The microalgae have garnered significant attention for carbon capture due to their potential in achieving carbon neutrality. These microorganisms possess the ability to utilize carbon dioxide and convert it into organic compounds through autotrophic growth under light conditions (Zhang et al., 2020). Yang et al. (2024) proposed that concentrated CO_2 is commonly found in flue gas, presenting opportunities for algae cultivation. However, this approach faces challenges such as mass transfer limitations and poor CO_2 dissolution, hindering the achievement of optimal algal growth levels at given flue gas concentrations. Bicarbonate can serve as a flexible carbon source with the potential to enhance the efficiency of biological carbon fixation by algae. Moreover, stringent requirements exist for selecting suitable algae strains. Therefore, system optimization plays a crucial role in improving the industrial scale-up of carbon capture and utilization (CCU) (Yang et al., 2024).

Researchers have recently investigated the potential of microalgae for soil improvement and as inhibitors to mitigate atmospheric sandstorms. Traditionally, algae have been associated with aquatic environments; however, algal species found in soils from arid and semi-arid regions are commonly identified through gene sequencing analysis and morphological characterization. The formation of algae-based biological soil crusts (BSCs) involves four sequential stages: initial attachment of algal cells, subsequent secretion of extracellular polymeric substances (EPS), co-growth with other microorganisms, and eventual thickening of the BSC (Lu et al., 2022). Regarding soil enrichment, microalgae can enhance plant productivity comparably to traditional chemical nitrogen fertilizers. Additionally, microalgae serve as a valuable phosphorus source for crops, facilitating phosphorus recovery. Most microalgal species prefer inorganic phosphate (PO_4^-) over organic phosphate compounds (Dagnaisser et al., 2022).

In addition, for the sake of improving dust suppression, a new method for extracting microalgae oil to synthesize coal dust suppressants is proposed to address the poor performance of traditional suppressants under hard water conditions. The optimal extraction conditions were determined through experiments, and a microalgae oil-based dust suppressant (MODS) was synthesized. MODS showed good hard water resistance, maintaining low surface tension and better wettability compared to sodium dodecyl benzene sulphonate (SDBS). This study provides a foundation for developing green and hardwater-resistant coal dust suppressants (Wang et al., 2023).

4 Future perspective

Despite advancements in enhancing microalgae utilization, achieving large-scale production at a low cost while generating high-value byproducts remains a significant challenge. While the preceding discussion focused on technological advancements, certain concerns warrant attention. One such concern is operational safety. Recent studies have highlighted the risk of microbial escape during aeration in wastewater treatment processes, which could allow potential pathogens to enter the air and pose health risks to humans (Wang et al., 2024). Additionally, suspended algae have been detected in the atmosphere in natural environments (Dey et al., 2024), and indoor dust containing algae has been found on air conditioners (Nie et al., 2023). Given that open pond cultivation is widely used, it is essential to consider the potential presence of airborne pathogens alongside algal growth.

5 Conclusion

Microalgae, based on advanced technology, remains a promising candidate for achieving sustainable production. To address the issue of high cost, it is crucial to consider multiple applications, including the utilization of valuable by-products and its eco-friendly potential in agriculture, among others. Furthermore, incorporating state-of-the-art techniques such as recombinant CRISPR-Cas9 technology, AI and omics can expedite the optimization of growth conditions and enhance output efficiency. Finally, the implementation of airborne pathogen control measures during microalgae cultivation is also proposed to ensure the health and safety of workers.

Author contributions

YQ: Writing – original draft, Formal Analysis, Writing – review and editing. TL: Writing – review and editing, Formal Analysis. CN: Writing – review and editing, Funding acquisition, Supervision, Formal Analysis. XG: Writing – review and editing, Funding acquisition. XS: Writing – review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

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