

Algae Bioenergy: A New Power Source for Sustainable Development

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Abstract Algae bioenergy is a kind of bioenergy made of algae as raw materials, which can replace liquid fossil fuels. Meanwhile, algae is also a substitute for common biofuel raw materials such as corn (*Zea mays*) and sugarcane (*Saccharum officinarum*). At present, many governments and private enterprises in countries have begun to study how to reduce the production cost of algae bioenergy for commercial applications. Like fossil fuels, algae bioenergy also produces carbon dioxide during combustion, but unlike fossil fuels, algae can absorb natural carbon dioxide through photosynthesis during their growth process. Therefore, using algae bioenergy can achieve carbon dioxide reduction. This review introduces the species of algal bioenergy, analyzes its sustainability, future application and development trend, so as to better understand its potential and limitations.

Keywords Algal fuel; Biofuels; Sustainable development

As the world's population continues to grow and economies develop rapidly, the demand for energy is constantly increasing, leading to a rise in the consumption of traditional fossil fuels. However, the use of conventional energy sources has caused severe pollution and environmental damage, highlighting the urgent need for the development of a clean and renewable alternative. Algal bioenergy, as an emerging clean energy source, holds vast application prospects and is becoming a new driving force for sustainable development (Chen, 2021).

Over the past few decades, the importance of bioenergy has been recognized. Compared to traditional fossil fuels, bioenergy offers numerous advantages, such as renewability, non-toxicity, harmlessness, lack of pollution, and low carbon emissions. Among them, algal bioenergy, as an emerging form of bioenergy, has garnered increasing attention in recent years.

Algae are microaquatic organisms that can exist as single-celled or multicellular forms. They have short growth cycles, rapid growth rates, and the ability to thrive and reproduce in various natural environments. Algal bioenergy is a clean energy source derived from algae, and compared to other bioenergy sources, it boasts higher yields, greater energy density, and lower production costs.

The prospects for the development of algal bioenergy are extensive. Algae can harness solar energy through photosynthesis to convert it into chemical energy, producing various useful chemical substances such as biofuels, biodiesel, biomethanol, and biohydrogen. Algal bioenergy can find applications not only in transportation, construction, and industries but also in areas like environmental protection, agricultural production, and aquaculture.

However, the development of algal bioenergy faces challenges and issues. The most significant challenge is the high production cost and low efficiency. Additionally, the sourcing of raw materials for algal bioenergy production presents certain problems. For instance, algal cultivation is heavily influenced by environmental factors, and utilizing algae for bioenergy production involves several technical challenges.

This review will explore various aspects related to the sustainable development of algal bioenergy. It will analyze and study aspects such as the background of algal bioenergy, production technologies for algal bioenergy, the role of algal bioenergy in global energy transition, and strategies for the sustainable development of algal bioenergy.

The aim of this review is to provide reference and guidance for the sustainable development and application of algal bioenergy, promoting its clean, sustainable, and intelligent utilization. Through in-depth research, we aspire to provide scientific basis and technological support for the advancement of algal bioenergy, contributing to the realization of energy transition and sustainable development goals.

1 Overview of Algal Bioenergy

1.1 Origins of algal bioenergy

The concept of algal bioenergy first emerged in 1942 when Harder and von Witsch proposed using microalgae as a source of lipids for food or fuel. After World War II, countries including the United States, Germany, Japan, the United Kingdom, and Israel began researching large-scale cultivation techniques and engineering systems for growing microalgae, particularly in the genus *Chlorella*. Furthermore, H.G. Aach demonstrated that protein nucleated *Chlorella* could accumulate lipids up to 70% of its dry weight through nitrogen starvation induction. As the post-war demand for alternative transportation fuels decreased, the focus shifted towards cultivating algae for food sources or wastewater treatment.

In the 1970s, due to oil embargoes and soaring oil prices, interest in algal biofuels was reignited. In 1978, the U.S. Department of Energy initiated the Aquatic Species Program, investing \$25 million over 18 years to develop liquid fuels competitive in price with petroleum from algae. The program primarily cultivated microalgae in open outdoor ponds, which was cost-effective but susceptible to environmental disruptions such as temperature fluctuations and biological invasions. Notably, it was discovered that fast growth and high lipid production could not be achieved simultaneously, as the former required high nutrients while the latter required low nutrients. The final research report suggested the necessity of genetic engineering to overcome this challenge and other natural limitations. Although experiments confirmed the feasibility of large-scale algae fuel production in outdoor ponds, it could not compete with petroleum in terms of cost. Particularly, during the 1990s, the price of unpurified algal oil ranged from \$59 to \$186 per barrel, while petroleum prices were less than \$20 per barrel in 1995. Due to budget pressures, the Aquatic Species Program was terminated in 1996.

Other diverse applications of algae cultivation contributed to the research on algal biofuels. For instance, in the 1990s, the Research Institute of Innovative Technology for the Earth (RITE) in Japan executed a project to develop systems for algae-based carbon dioxide fixation. Although energy production wasn't their goal, several studies indicated that flue gases from power plants could be used as a carbon dioxide source for algae cultivation, a significant advancement in algal biofuel research. Other studies focused on harnessing hydrogen, methane, or ethanol from algae, as well as developing nutritional supplements and pharmaceutical compounds, also contributing to the progress of algal biofuel research.

Following the dissolution of the Aquatic Species Program in 1996, research on algal biofuels experienced a period of stagnation. Today, rising oil prices have renewed interest in algal biofuels. Increased funding from the U.S. federal government, along with support from research projects in Australia, New Zealand, Europe, the Middle East, and other regions globally, has propelled the field forward. Additionally, some private companies have entered the field as well.

1.2 Types and production methods of algal bioenergy

Algal bioenergy refers to the production of bioenergy using algae as the raw material. It is a renewable, green, and environmentally friendly energy source (Zhu et al., 2018). Currently, algal bioenergy can be categorized into three types: biodiesel, bioethanol, and biogas.

Biodiesel is a biofuel derived from algal oils as an alternative to fossil fuels (Figure 1). Algal oils can be obtained through direct extraction or conversion of algal biomass. Certain algal species can produce up to 60% or more of their dry weight in oil. There are numerous types of algae suitable for oil production, including diatoms, green algae, and golden algae. These algae can be cultivated through various growth methods and bioreactors to yield substantial biomass and usable oil, which can then be converted into biodiesel. Biodiesel possesses high energy density, excellent combustion properties, and minimal pollution emissions. It can replace traditional fossil diesel and holds significant potential for applications in aviation, transportation, and other sectors.



Figure 1 Green jet fuel made from algae (Photo from Baidu)

Bioethanol is a biofuel produced through fermentation of algae. Algal species used for ethanol production primarily include brown algae, red algae, and green algae. These algae absorb carbon dioxide through photosynthesis and convert it into ethanol through fermentation (Bao, 2017). Bioethanol offers advantages such as high energy density, eco-friendliness, and renewability. It can serve as an alternative to conventional fossil-based ethanol and holds a wide range of applications in transportation, chemical industries, and more.

Biogenic gas, including biogas and hydrogen, is a type of biofuel made from algae. Biogas is mainly composed of methane (CH₄) and carbon dioxide (CO₂) (Zhang et al., 2023), as well as a small amount of hydrogen sulfide, oxygen, nitrogen, and hydrogen. Large algae exhibit higher methane production compared to plant biomass. Biogas is produced primarily through anaerobic digestion of algal biomass or catalytic gasification, a high-temperature (usually between 800 °C and 1 000 °C) process that partially oxidizes hydrocarbons into synthesis gas. Hydrogen gas can be generated through algal photosynthesis. Biogas is clean, renewable, and boasts a high energy density. It can be directly burned for energy production or used as fuel for turbine engines. It holds promising applications in the energy and chemical sectors.

As an emerging sustainable energy source, algal bioenergy holds significant application prospects and research value. In-depth study of the types and production methods of algal bioenergy can provide a better understanding of its advantages and limitations, offering scientific basis and technical support for research and application endeavors.

1.3 Advantages of algal bioenergy

Algal bioenergy possesses numerous advantages that have multifaceted significance, including high yield, no land occupation, promotion of environmental protection, enhanced waste and wastewater treatment efficiency, increased agricultural and aquacultural value, among others. It can not only replace traditional fossil fuels, reducing environmental pollution, but also stimulate economic development and employment, accelerate energy transition and sustainable development, foster ecosystem conservation and restoration, and enhance energy security and national strategy. These merits make algal bioenergy a highly regarded new and sustainable energy form, with broad application prospects and substantial research value.

Algae are highly efficient photosynthetic organisms with rapid growth rates and high biomass yield (Figure 2). Unlike common terrestrial energy plants that yield crops once or twice a year, algae can yield generations within days without ecological disruption (Bull and Collins, 2012). Their unit yield per area is dozens of times that of maize (*Zea mays*). Compared to traditional biomass energy sources, algal bioenergy boasts higher biomass yield and energy density, greatly improving production efficiency and energy utilization (Gu et al., 2011). Moreover, algae exhibit exceptionally high oil production rates. Some algal species can contain as much as 20% to 70% lipid content, resulting in annual oil production per unit area approximately 552 times that of maize, 213 times that of soybeans, and 80 times that of rapeseed.



Figure 2 Algae bioenergy (Photo from 58pic)

Algal bioenergy production requires no arable land and has low environmental demands, thriving in various growth environments such as seawater, freshwater, saline-alkali land, swamps, and fish ponds. Cultivating algae utilizes different water resources like oceans, sewage, and waste, reducing competition for and occupation of land resources.

During their growth, algae naturally absorb carbon dioxide from the environment, contributing to greenhouse gas reduction. Studies have shown that replacing fossil fuels with renewable energy sources like biofuels can lead to an 80% reduction in carbon dioxide emissions. Algae-based systems can capture approximately 80% of carbon dioxide emissions from power plants in sunlight. Additionally, algae are sulfur-free and produce non-toxic and non-harmful gases during combustion, rendering the oil extraction process exceptionally clean. The substitution of traditional fossil fuels with algal biofuels reduces emissions of harmful gases such as carbon dioxide and nitrogen oxides during combustion, thus alleviating atmospheric pollution (Wang and Chen, 2011).

Algae possess a strong capacity to absorb organic compounds from waste and sewage (Menetrez, 2012), effectively converting them into biomass. Algal biomass production can enhance waste and wastewater treatment efficiency while yielding renewable bioenergy.

By producing biomass and biofuels through algae, added value can be created for agriculture and aquaculture. Waste and byproducts from algal production can be used as fertilizers and feed, increasing agricultural output. Simultaneously, algal biomass can serve as feed for aquaculture, enhancing aquacultural efficiency.

Algal bioenergy production and utilization can foster economic development and employment. The interdisciplinary nature of algal production, involving biology, chemistry, and engineering, presents ample opportunities for industry development, job creation, and contributions to societal and economic progress (Yu, 2010).

Algal bioenergy production and utilization can accelerate energy transition and sustainable development. Beyond substituting traditional fossil fuels and mitigating environmental pollution, algal bioenergy can reduce dependence on energy sources and significantly contribute to energy sustainability.

Furthermore, algal bioenergy production and utilization can promote ecosystem protection and restoration. The carbon dioxide consumed during algal growth reduces atmospheric carbon dioxide levels, alleviating atmospheric pressure. Algae can also absorb pollutants and harmful substances, purifying water and soil, and promoting ecosystem recovery and preservation.

Lastly, algal bioenergy production and utilization can enhance energy security and national strategy. Algal production requires no arable land and can be conducted in places like oceans without depleting finite land resources, reducing reliance on imported fossil fuels like petroleum and enhancing national energy security. Meanwhile, algal bioenergy can play a vital role in national energy strategies, accelerating energy transition and sustainable development processes.

2 Sustainable Analysis of Algal Bioenergy

2.1 Life cycle assessment

Algal bioenergy, being renewable and low-carbon, boasts multiple advantages; however, its production and utilization unavoidably impose certain environmental impacts. Therefore, assessing the sustainability of algal bioenergy is essential. Life Cycle Assessment (LCA) is a method used to evaluate the environmental impact of a product or service throughout its entire lifecycle. LCA for algal bioenergy involves assessing environmental impacts across various stages, including energy input, production, transportation, usage, and waste disposal. By evaluating these stages, both the strengths and limitations of algal bioenergy can be identified, providing a scientific basis for formulating sustainable strategies for its production and utilization.

Energy input refers to the energy required for producing algal bioenergy, including the consumption of water, electricity, and heat. In terms of energy input, algal bioenergy requires lower energy input compared to traditional biomass energy, as its production does not require arable land and minimizes the use of water resources and agricultural inputs like fertilizers.

Production entails the process of producing algal bioenergy, which involves algae cultivation, harvesting, lipid extraction, and more. During the algae cultivation phase, significant amounts of freshwater or seawater are used, along with energy sources such as solar energy and electricity. The harvesting and lipid extraction phases require the use of certain chemicals and energy sources, such as organic solvents and electricity. Additionally, the production process generates waste, such as algal biomass residues (Figure 3).

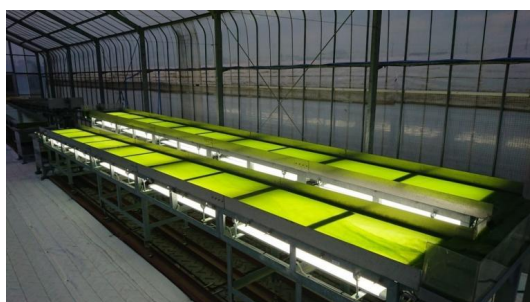


Figure 3 Production and cultivation of algae (Photo from Baidu)

Transportation refers to the process of transporting algal bioenergy from the production site to the usage site. During transportation, energy, labor, and resources are consumed, and greenhouse gases such as carbon dioxide are emitted.

Usage pertains to the impact of algal bioenergy on the environment during its application. Algal bioenergy is primarily utilized for power generation or as a substitute for traditional fossil fuels. During usage, algal bioenergy does not emit harmful gases such as carbon dioxide or nitrogen oxides, resulting in minimal environmental impact.

Waste disposal refers to the environmental impact of waste generated during the processing of algal bioenergy. The production process of algal bioenergy generates waste materials such as algal biomass residues and extraction liquids. These waste materials have an impact on the environment, such as soil and water pollution. In the future, enhanced waste management practices like biodegradation and recycling can be employed to minimize the environmental impact of algal bioenergy waste.

2.2 Footprint analysis

In addition to life cycle assessment, footprint analysis is also a crucial method for assessing sustainability. By evaluating algal bioenergy from the perspectives of ecological footprint, carbon footprint, and water footprint, it is possible to reflect the impact of its production and utilization on the ecological environment. This approach represents a comprehensive assessment method. In the future, a series of measures, such as reducing energy consumption, minimizing transportation distances, and enhancing waste management, will be necessary to reduce

the carbon footprint of algal bioenergy. Simultaneously, optimizing production techniques and improving the cultivation environment of algae are essential for enhancing the water resource utilization efficiency of algal bioenergy. These measures hold significant importance for driving the sustainable development and application of algal bioenergy.

Ecological footprint refers to the ecological resource area required by a country, region, or organization, including the area needed for resource consumption and waste treatment. Ecological footprint assessment can reflect the impact of algal bioenergy production and utilization on the ecological environment, making it a comprehensive assessment method.

Carbon footprint refers to the total amount of greenhouse gas emissions produced by a product or service throughout its lifecycle. While the production process of algal bioenergy does not directly generate greenhouse gases like carbon dioxide, certain amounts of greenhouse gas emissions are produced in stages such as energy input, transportation, and waste management. Therefore, assessing the carbon footprint of algal bioenergy is one of the important indicators for measuring its sustainability. In the future, measures such as reducing energy consumption, minimizing transportation distances, and strengthening waste management need to be implemented to lower the carbon footprint of algal bioenergy.

Water footprint refers to the amount of water resources consumed by a country, region, or organization in the production and consumption processes. The production process of algal bioenergy requires a significant amount of water resources, especially during the algae cultivation phase, where water resource utilization efficiency is relatively low. Consequently, assessing the water footprint of algal bioenergy is another crucial indicator for measuring its sustainability. In the future, measures like optimizing production techniques and improving the cultivation environment of algae should be taken to enhance the water resource utilization efficiency of algal bioenergy.

2.3 Other sustainability analyses

The sustainability assessment of algal bioenergy requires a comprehensive evaluation using various methods to gain a thorough understanding of its environmental and societal impacts throughout its lifecycle. In addition to life cycle assessment and footprint analysis, the sustainability assessment of algal bioenergy also needs to consider its energy efficiency and impacts on ecosystems and society. By implementing appropriate measures, the sustainability of algal bioenergy can be enhanced, providing support for its sustainable development.

The production process of algal bioenergy requires the input of certain forms of energy, such as electricity and light energy. Therefore, evaluating energy efficiency is one of the important indicators for measuring the sustainability of algal bioenergy. Currently, the energy efficiency of algal bioenergy is relatively low, especially in stages like algae cultivation and harvesting, where issues of high energy consumption and low efficiency exist. Hence, in the future, it's necessary to further improve the production efficiency of algal bioenergy, reduce energy consumption, and enhance energy utilization efficiency.

The production process of algal bioenergy requires a certain amount of land and water resources, which may have certain impacts on surrounding ecosystems, such as impacts on aquatic ecosystems and wildlife. In the future, measures such as optimizing production techniques and selecting suitable production areas can be taken to reduce the impact of algal bioenergy on ecosystems.

The production and utilization of algal bioenergy may have certain impacts on local society, such as employment and economic development. To promote the sustainable development of algal bioenergy and reduce negative impacts on society, it's important to strengthen assessments of social impacts, establish sound production and utilization standards, and ensure that the positive impacts of algal bioenergy on local society are secured.

3 Technology Innovation

With the continuous growth in global energy demand and increasing concerns about traditional fossil fuels, algal bioenergy has garnered significant attention as a sustainable alternative. Innovations in algal bioenergy technology

span various aspects and require ongoing research and exploration to enhance biomass yield, extraction efficiency, energy conversion, and other technologies, thereby driving the commercial development of algal bioenergy.

3.1 Bioreactor design

Bioreactors are pivotal devices for algal biomass production and energy conversion. To increase biomass yield and energy conversion efficiency, researchers have focused on refining bioreactor design to achieve precise control and optimization of algal growth conditions. For instance, through coordinated regulation of parameters like light intensity, temperature, CO₂ concentration, and oxygen content, significant improvements in algal biomass yield and lipid content can be achieved. The use of an automated control system that adjusts parameters such as light intensity, temperature, CO₂ concentration, and oxygen content in combination can significantly enhance algal biomass yield and lipid content. An automated control system based on a PID control algorithm, for example, can monitor and adjust parameters like light intensity, temperature, CO₂ concentration, and oxygen content periodically, enabling optimal algal growth conditions and subsequently enhancing biomass yield and lipid content.

3.2 Algal breeding

The variety and genetic characteristics of algae significantly influence properties such as biomass yield and lipid content. To enhance algal biomass and lipid production, researchers have employed techniques like gene editing and genomics to genetically improve and breed algae. For instance, utilizing CRISPR-Cas9 technology allows precise editing and regulation of crucial genes within algae, achieving accurate control over biomass and lipid production. Furthermore, utilizing CRISPR-Cas9 technology to edit and regulate genes related to fatty acid metabolism in algae can significantly enhance lipid content. Gene editing tools based on CRISPR-Cas9 technology enable precise control over algal lipid content by targeting genes involved in fatty acid metabolism.

3.3 Biomass extraction

Biomass extraction involves separating and extracting valuable compounds such as lipids, proteins, and carbohydrates from algae. To enhance extraction efficiency, researchers have developed various extraction methods, including ultrasound-assisted extraction, distillation, and solvent extraction. Additionally, optimization of extraction conditions, such as solvent type, concentration, temperature, and time, has been studied to improve extraction efficiency and reduce costs.

3.4 Energy conversion

Energy conversion entails the transformation of algal biomass into usable energy. Common energy conversion technologies include biofuel cells, biological hydrogen fermentation, and conversion of algal oil into biodiesel. To enhance energy conversion efficiency, researchers continually refine reactor design, optimize reaction conditions, and improve catalysts to increase efficiency and reduce costs.

4 Challenges and Opportunities

4.1 Commercialization cases of algal bioenergy

As a promising industry for sustainable development, algal bioenergy has been gaining significant global attention. There are several successful cases of commercialization in the field of algal bioenergy. These cases not only highlight the vital role of algal bioenergy in environmental protection and energy transition but also inspire further research and applications, contributing to the sustainable development of the bioenergy industry.

Founded in 2007, Sapphire Energy is a US-based algal bioenergy company. It employs proprietary algal cultivation systems to produce high-quality biodiesel and protein powder. The company has research facilities in Las Cruces, New Mexico, and established its first integrated algal bio-refinery in Columbus, New Mexico (source: <https://www.crunchbase.com/organization/sapphire-energy>). Starting in March 2013, Sapphire Energy commenced commercial sales of algal biofuel to Tesoro (source: <https://www.hisour.com/algae-fuel-40891/>).

Established in 2007, Algae.Tec is an Australian algal bioenergy company focused on commercializing algal production technologies for sustainable products, including protein and oil such as biofuel. With an experienced

global team, Algae.Tec possesses over 200 years of combined technical, professional, and business expertise in key energy and environmental sectors. The company's strengths lie in algal production, biofuel technology, energy markets, project commercialization, and business management. Algae.Tec has formed strategic partnerships with companies like Manildra Group, Lufthansa, Holcim Lanka, and Shandong Kerui Holding Group (source: <https://renewable-carbon.eu/news/algae-tec-algae-for-nutraceutical-products/>).

OriginOil, headquartered in Los Angeles, California, was founded in 2007. It is a US-based algal bioenergy company dedicated to developing energy production processes for harvesting algae and cleaning oil and gas water. Leveraging proprietary algal oil extraction technology, OriginOil produces high-quality biodiesel and other high-value products. The company embeds its technology into systems through joint ventures, proprietary brands, and licensing agreements. The OriginOil system controls algal harvest, enabling other companies to convert it into biocrude, biogas, or bio-carbon for refining into fuels and chemicals; it also separates lipids and biomass for further processing into valuable products (source: <https://www.shaleexperts.com/company/Originoil-Inc>).

During the commercialization process, different companies have adopted distinct business models. For instance, Sapphire Energy follows a production and sales model, selling its proprietary algal bioenergy products to other companies. On the other hand, Algae.Tec employs a technology licensing model, granting other companies the right to use its proprietary algal production technology.

The success of these companies illustrates that algal bioenergy has entered the commercialization stage. It also underscores the importance of ongoing exploration and innovation in the commercialization process to promote the development and adoption of algal bioenergy, advancing the commercialization of algal bioenergy.

4.2 Challenges remained

As an emerging energy source, the commercialization of algal bioenergy is bound to encounter a multitude of challenges and opportunities. It requires support and advancement across various fronts such as policy, technology, and market to achieve sustainable development and commercialization. Additionally, efforts to enhance environmental protection and public awareness are crucial to improve public understanding and acceptance of algal bioenergy and facilitate its commercialization.

At present, the algal bioenergy industry faces several technical difficulties and bottlenecks (Wang and Chen, 2011). These primarily include: (1) Algal breeding, forming the foundation of the algal bioenergy chain, remains a challenge in achieving efficient breeding; (2) Cultivation of algae, a critical aspect, requires technological innovation and economies of scale to address high production costs and long growth cycles for enhanced commercial competitiveness; (3) Increasing algal biomass and production efficiency is key to algal bioenergy commercialization, necessitating continuous exploration and optimization of production techniques to enhance efficiency and economic benefits (Ruffing et al., 2022); (4) Algae rely on light energy for photosynthesis, yet their light energy utilization efficiency is low. Therefore, continuous exploration and optimization of production techniques are essential to enhance light energy utilization efficiency and boost production efficiency and economic benefits; (5) Algal harvesting and extraction, crucial in the production process, need solutions for high harvesting and extraction costs, as well as low efficiency.

The high production cost and low energy conversion efficiency of algal bioenergy require cost reduction strategies, funding support, and improved commercial competitiveness. Additionally, the market demand for algal bioenergy presents its own set of challenges, necessitating intensified efforts in market promotion and advertising to enhance consumer awareness and acceptance. The commercialization of algal bioenergy requires substantial financial support, necessitating attracting more investment and establishing a robust financing system to propel its commercialization. The need for expanded market demand for algal bioenergy also calls for enhanced marketing efforts and public education to boost consumer awareness and acceptance. The construction of the algal bioenergy industry chain, encompassing aspects like algal breeding, production, extraction, and energy conversion, needs continuous improvement to enhance production efficiency and reduce costs.

The commercialization of algal bioenergy must also address societal issues, such as environmental protection and public awareness and acceptance. Despite the advantages of algal bioenergy like renewability and low carbon emissions, its commercial prospects are still hindered by insufficient market demand. Given the affordability of traditional energy sources, market demand continues to center around conventional fuels, and the market demand for algal bioenergy remains relatively untapped. Currently, public awareness and acceptance of algal bioenergy are relatively low, necessitating increased promotional and educational efforts to enhance public understanding and acceptance, thereby driving its commercialization.

The commercialization of algal bioenergy also requires addressing environmental concerns arising from algal production, such as impacts on water and land resources. Algal bioenergy production requires substantial water resources, warranting exploration and innovation in water resource management and utilization. Similarly, it necessitates the utilization of significant land resources, demanding innovation and exploration in land resource management and utilization. Algal bioenergy production also generates environmental issues such as wastewater and emissions, requiring strengthened environmental protection and control to reduce pollution and ecological damage. Currently, further research and solutions are needed to address the impact of algal production on water and land resources to ensure the sustainable development of algal bioenergy.

4.3 Development prospects

As an emerging sustainable energy source, algal bioenergy holds numerous potential opportunities. These include substituting traditional fossil fuels, promoting agricultural development, enhancing energy security, and reducing carbon emissions. Algal bioenergy is poised to become a vital component of future sustainable development and energy structure transformation. With support and advancement from technology, market dynamics, policy frameworks, and more, the commercialization of algal bioenergy offers vast development prospects. It will bring new opportunities and challenges to humanity's energy development and environmental protection, facilitating the achievement of sustainable development and environmental conservation goals.

Algal bioenergy can serve as a substitute for traditional fossil fuels such as oil, coal, and natural gas, with attributes like renewability, cleanliness, and low carbon emissions. The commercial development of algal bioenergy holds the potential to reduce reliance on conventional fossil fuels, stimulate energy structure transformation, and encourage sustainable development. Furthermore, it can also contribute to agricultural advancement. Algal bioenergy production necessitates significant water and carbon dioxide resources, which can be sourced from agricultural lands and ponds. Simultaneously, waste generated during the production process can be used as organic fertilizers, fostering agricultural development and ecological construction.

Algal bioenergy production is not constrained by geographical limitations; it can occur globally. Compared to traditional fossil fuels, algal bioenergy offers more stable supply and higher energy security, potentially reducing dependence on energy imports and enhancing energy security levels. Algal bioenergy is a low-carbon energy source, capable of absorbing substantial amounts of carbon dioxide during its growth phase. Additionally, the carbon emissions generated during its energy conversion process are lower compared to traditional energy sources. The commercial development of algal bioenergy holds the potential to mitigate the impact of global climate change, promoting carbon reduction and environmental improvement.

Algal bioenergy production involves multiple technological fields, including biotechnology, chemical engineering, environmental science, and more. Driving the commercial development of algal bioenergy requires continuous technological innovation and scientific advancement. Simultaneously, the development of algal bioenergy will also catalyze innovation and advancement in related fields, fostering technological and industrial upgrades (Yang and Wang, 2013).

The commercial development of algal bioenergy has the potential to stimulate economic growth and create employment opportunities. Various aspects of algal bioenergy production, from breeding and cultivation to extraction and energy conversion, require human resources and technical support. The development of algal bioenergy can stimulate the growth of related industry chains and expand job opportunities, benefitting society.

Algal bioenergy is a global energy source with vast market potential, and its commercial development can enhance a country's international competitiveness. Against the backdrop of global energy transition, the development of algal bioenergy can help countries secure advantageous energy positions, elevate energy competitiveness, and enhance international influence.

5 Outlook

Algal bioenergy, as an emerging sustainable energy source, presents advantages of sustainability and environmental friendliness, positioning it as a pivotal direction for future energy transition. While the technological innovation and commercial progress of algal bioenergy are continuously advancing, challenges and difficulties in technical, economic, social, and environmental aspects persist. Algal bioenergy continues to hold a broad scope of application and developmental potential. Its commercialization is poised to alleviate energy crises, reduce carbon emissions, create employment opportunities, and stimulate economic growth.

In future research and development endeavors, it is imperative to enhance the production efficiency and light utilization rate of algal bioenergy while simultaneously lowering production costs. Moreover, increased efforts in market promotion and societal awareness are essential to elevate public recognition and acceptance of algal bioenergy, thereby propelling its commercialization. Simultaneously, as the commercialization of algal bioenergy advances, strengthened environmental protection and management are necessary, including reducing carbon and water footprints associated with algal bioenergy production to minimize ecological pollution and degradation. Additionally, reinforcing international exchanges and collaborations to explore the diverse applications of algal bioenergy in other sectors, such as food, pharmaceuticals, and cosmetics, would contribute to the internationalization and industrialization of algal bioenergy. This approach facilitates the multifaceted utilization of algal bioenergy, expands market dimensions, enhances commercial value, and augments economic benefits.

Authors' contributions

YSY was the initiator and principal investigator of this study, responsible for conceptualizing the research and drafting the initial manuscript.

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