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Review

Life Cycle Assessment of Microalgal Carbon Fixation and Torrefaction for Carbon Neutralization: A State-of-the-Art Review

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Abstract: In the past decades, a series of phenomena such as global warming, glacier melting, sea level rise, and haze weather caused by the greenhouse effect have been reported, which seriously threaten the future of humans. To address this challenge, several countries have initiated interventions to prevent climate change, such as carbon neutralization. Given the current economic, social development and environmental protection requirements, microalgal carbon fixation appears to be a suitable approach to achieve carbon net zero emission while also promoting microalgal biofuel production. This promotes the realization of energy structure transformation and optimization of carbon neutralization. This article provides a comprehensive and state-of-the-art review of research progress on microalgal carbon capture and solid biofuel production via the torrefaction process, with focus on the efficiency and capacity of microalgal carbon fixation, as well as the principle and application of microalgal torrefaction. The detailed review includes the practical value and development prospect of microalgal torrefied biochar, fuel performance conversion, and mechanism in the torrefaction process. Furthermore, the environmental impact of microalgal carbon fixation and torrefaction process are discussed to evaluate the overall environmental benefits of microalgal utilization via life cycle assessment (LCA) method. The technical difficulties of microalgal carbon fixation and torrefaction process are also discussed. This review paper is beneficial to guide the scheme demonstration and specific implementation of microalgal carbon neutralization and thus lead to the efficient establishment of microalgal carbon reduction, biomass accumulation, and biofuel production techniques.

Keywords: life cycle assessment; microalgal carbon fixation; microalgal torrefaction; integrative analysis; carbon neutralization

1. Introduction

Microalgae, also known as microscopic algae, are tiny photosynthetic organisms found in various aquatic environments, such as freshwater and marine habitats [1]. They are single-celled or multicellular organisms belonging to various microorganisms called algae. Microalgae carry out photosynthesis, using sunlight as the energy source to convert carbon dioxide (CO_2) and water into organic compounds, primarily sugars and oxygen (O_2) [2]. They are involved in global carbon fixation, producing a significant volume of O_2 and removing CO_2 from the atmosphere. Microalgae can be widely used in various fields, such as food, feed, biofuels, cosmetics, medicine, etc [3]. In recent years, the application of microalgae in the energy field has received increasing attention. Due to the absorption of a large amount of CO_2 during the growth process of microalgae, they can be converted into solid biofuels through the pyrolysis process. Thus, the microalgae can be used to achieve carbon neutralization and renewable energy [4,5].

Microalgal carbon fixation refers to the process in which microalgae absorb a large amount of CO_2 through photosynthesis, convert it into organic matter, and fix it in biomass [6]. Microalgae can efficiently convert CO_2 from the atmosphere into organic carbon and store it within cells, making it a vital carbon storage medium [7]. This process not only helps to reduce the concentration of CO_2 in the atmosphere, but also sustainably sequesters carbon during the utilization of microalgal biomass. Microalgae possess the following advantages in carbon fixation: (1) Compared to other plants, microalgae possess higher photosynthetic efficiency and can more effectively absorb CO_2 from the atmosphere [8]. (2) Microalgae possess the characteristic of rapid growth, which can quickly accumulate a large amount of biomass and fix a large amount of carbon inside the cells. (3) Microalgae are classified into numerous species, each with unique adaptability under different environmental conditions, exhibiting significant potential for carbon sequestration [9]. (4) The growth of microalgae is a renewable process, and its biomass can be utilized to produce a range of valuable products, including food, feed, and biofuels. This makes its carbon fixation process more sustainable. Due to its efficient absorption of CO_2 and rapid growth, microalgae carbon fixation is considered a potential carbon neutralization technology [10]. Utilizing microalgae to fix and store carbon helps reduce CO_2 concentration in the atmosphere, alleviate the global greenhouse effect, and provide a sustainable solution for addressing climate change.

Microalgal torrefaction is a process in which microalgae are thermally treated in the absence of O_2 at 200–300 °C. This process aims to improve microalgal biomass's properties and energy density for efficient conversion into biofuels or other valuable products [11]. During microalgal torrefaction, the biomass undergoes various physical and chemical changes. The process typically involves the removal of moisture and volatile matter, resulting in increased carbon content and energy density [12]. The main objectives of microalgal torrefaction are increasing the energy density, improving stability and handling, and enhancing conversion efficiency. It is important to note that microalgal torrefaction is still an emerging technology, and further research and development are needed to optimize the process parameters, understand the effects on different microalgal species, and evaluate the overall techno-economic feasibility [13]. Nonetheless, microalgal torrefaction holds potential as a sustainable and renewable pathway for energy production and utilization of microalgal biomass.

Combining microalgal carbon fixation and microalgal torrefaction can potentially achieve carbon neutralization or even carbon negative effects [14]. Microalgae are photosynthetic organisms that can capture CO_2 from the atmosphere and convert it into organic biomass through photosynthesis. The process involves utilizing sunlight, water, and CO_2 to produce carbohydrates, lipids, and proteins [15]. Cultivating microalgae in large-scale systems can fix and store significant amounts of CO_2 within the microalgal biomass [16]. After microalgae have been cultivated and harvested, they can undergo torrefaction process. In such systems, the CO_2 emitted during energy production from torrefied microalgae is captured and recycled back into the microalgal cultivation process. This creates a continuous cycle where CO_2 is repeatedly fixed and utilized, resulting in a net zero or even negative carbon footprint [17]. Combining microalgal carbon fixation with microalgal torrefaction may yield a carbon neutral or negative effect. The captured CO_2 is effectively stored within the microalgal biomass, and the subsequent energy production does not contribute to additional CO_2 emissions when a closed-loop system is implemented.

Life cycle assessment (LCA) is a common method for evaluating the environmental effects of a product or process throughout its entire life cycle. When conducting an LCA analysis of the overall process of microalgal carbon fixation and microalgal torrefaction, several key aspects can be considered, including microalgal cultivation, harvesting and drying, torrefaction process, energy production, end-of-life options, and additional inputs and processes [18]. The LCA analysis may help to assess the overall environmental performance of the microalgal carbon fixation and torrefaction process, revealing its potential environmental benefits and identifying areas for further improvement [19]. It helps decision-makers evaluate the sustainability of the technology and make informed choices to minimize potential negative impacts on the environment.

2. Microalgal Carbon Neutralization of Fixation and Conversion

2.1. A Brief Introduction to Carbon Neutralization

Carbon neutralization is the process of balancing or offsetting carbon emissions by compensating for them through activities that remove or reduce an equivalent amount of CO_2 from the atmosphere. The primary goal of carbon neutralization is to achieve a net-zero carbon footprint, where the emissions produced are balanced by actions that actively remove or prevent the release of CO_2 [20]. Human activities, such as burning fossil fuels, deforestation, and industrial processes, contribute to the accumulation of greenhouse gases in the atmosphere, leading to global warming and climate change. Carbon neutralization aims to mitigate these effects by reducing and counterbalancing the CO_2 emitted into the atmosphere. Several approaches are used to achieve carbon neutralization [21]. One common method involves reducing emissions at their source through energy efficiency measures, transitioning to renewable energy sources, or adopting cleaner technologies. By minimizing the amount of carbon emissions generated, the need for offsetting is reduced [22].

Offsetting plays a crucial role in carbon neutralization by investing in projects or initiatives that remove or reduce CO_2 from the atmosphere. This can include activities such as afforestation (planting trees), reforestation, carbon capture and storage (CCS) technologies, or supporting renewable energy projects [23]. These actions can offset the remaining carbon emissions that cannot be eliminated directly. Various standards and certifications have been established to ensure the credibility and transparency of carbon neutralization efforts. These frameworks verify and certify the authenticity and impact of offset projects, ensuring that they genuinely contribute to carbon reduction or removal [24]. Carbon neutralization is vital to address climate change and achieve sustainability goals. It allows individuals, businesses, and organizations to take responsibility for their carbon emissions and actively contribute to a greener and more sustainable future [25]. Implementation of carbon neutralization measures at individual and collective levels may achieve a balanced carbon cycle and mitigate the harmful effects of climate change.

2.2. Carbon Neutralization Value of Microalgal Carbon Fixation

The carbon neutralization value of microalgal carbon fixation refers to the ability of microalgae to absorb and convert CO_2 into organic biomass through photosynthesis. This process helps to offset carbon emissions and reduce the overall concentration of CO_2 in the atmosphere, thus contributing to carbon neutralization. Microalgae are highly efficient in capturing and utilizing CO_2 due to their rapid growth rates and high photosynthetic activity [3]. They can fix significant amounts of CO_2, often surpassing other terrestrial plants in their carbon sequestration potential. It is estimated that microalgae can capture several times more CO_2 per unit area compared to traditional land-based crops like trees. Moreover, microalgal biomass obtained through carbon fixation can be utilized in various ways [26]. It can be converted into biofuels, such as biodiesel or bioethanol, serving as alternative and renewable energy sources. Additionally, microalgae can be used as a feedstock for producing food supplements, animal feed, fertilizers, and other valuable products. Therefore, microalgal carbon fixation has significant carbon neutralization value as it not only helps to reduce greenhouse gas emissions but also provides potential solutions for sustainable energy production and resource utilization.

The carbon neutralization value of microalgal carbon fixation depends on several factors, including microalgae species, growth conditions, and cultivation methods. Different species have varying carbon uptake rates, with some being more efficient than others [27]. The carbon fixation conditions of different microalgae are listed in Table 1. Optimizing growth conditions, such as light intensity, temperature, and nutrient availability, can further enhance carbon fixation capacity. Furthermore, the utilization of microalgal biomass can also contribute to carbon neutralization. Microalgae can be used as a feedstock for biofuels, such as biodiesel and bioethanol, replacing fossil fuel-derived alternatives. By using microalgal biomass as a renewable energy source, carbon emissions can be reduced [28]. Overall, microalgal carbon fixation has the potential to play a significant role in carbon neutralization efforts due to its ability to capture and convert CO_2 into biomass, and its versatile applications in various sectors.

Table 1. The carbon fixation conditions of different microalgae.

Microalgae Species	CO_2 Fixation Rate (g_{CO2} $L^{-1}\cdot d^{-1}$)	CO_2 Fixation Efficiency (%)	Biomass Productivity ($g_{biomass}$ $L^{-1}\cdot d^{-1}$)	Reference
Chlorella fusca LEB 111	0.23	35.70%	0.12	[29]
Chlorella sp. AT1	0.57	64.00%	0.24	[30]
Scenedesmus sp.	0.16	33.00%	0.08	[31]
Spirulina sp.	0.18	21.80%	0.10	[32]
Scenedesmus obliquus SA1	1.04	10.30%	0.55	[33]
Chlorella fusca	0.26	63.40%	0.14	[34]
Chlorella vulgaris	1.28	12.00%	0.36	[35]
Spirulina sp. LEB 18	0.10	15.80%	0.06	[36]
Coelastrum sp.	7.25	59.80%	0.27	[37]
Spirulina platensis	1.44	85.00%	0.43	[38]
Scenedesmus dimorphus	0.80	63.40%	0.44	[39]

2.3. Mechanism and Application of Carbon Fixation and Reduction by Microalgae

Microalgal carbon fixation is the process by which microalgae convert CO_2 from the atmosphere into organic compounds through photosynthesis. This process plays a crucial role in mitigating climate change by reducing the concentration of CO_2. The mechanism of carbon fixation by microalgae primarily involves the process of photosynthesis [40]. Microalgae, like other plants and algae, use sunlight, CO_2, and water to produce organic compounds through photosynthesis. The process steps are summarized as follows: (1) Absorption of sunlight. Microalgae utilize pigments, such as chlorophyll, to absorb sunlight energy [41]. (2) Carbon dioxide uptake. Microalgae extract CO_2 from the atmosphere or dissolved carbon sources in water. (3) Photosynthetic reaction. In the presence of sunlight and the enzyme RuBis CO (Ribulose-1,5-bisphosphate carboxylase/oxygenase), CO_2 is converted into organic compounds, primarily carbohydrates. (4) Oxygen release. As a byproduct of photosynthesis, microalgae release oxygen into their environment [42]. The profiles of microalgal carbon fixation and conversion are shown in Figure 1.

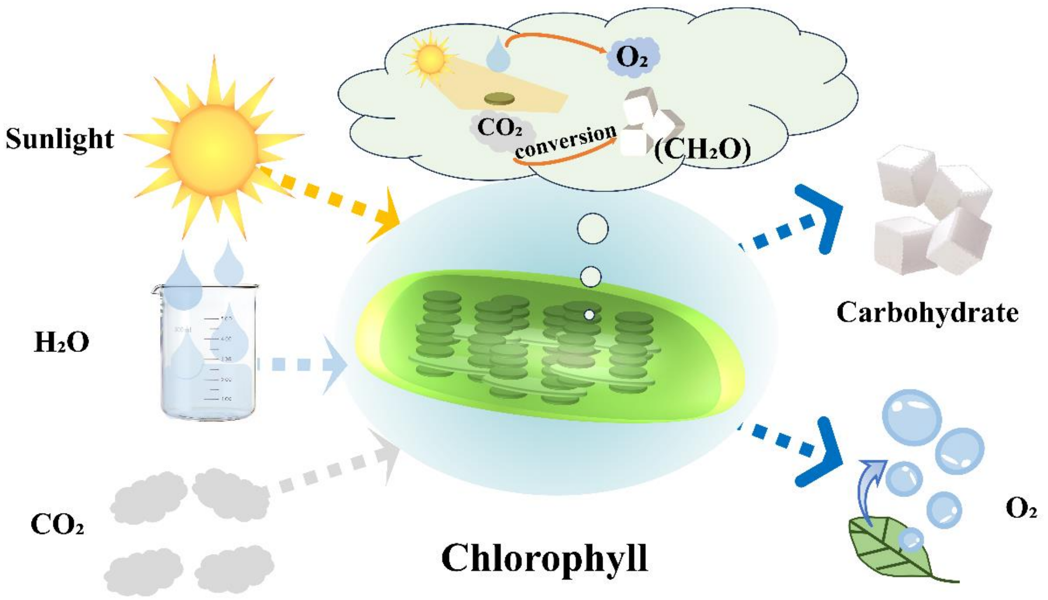

Figure 1. The profiles of microalgal carbon fixation and conversion.

Microalgal carbon fixation and reduction has multiple applications, including (1) Carbon sequestration. Microalgae can capture and store substantial amounts of CO_2, contributing to mitigating greenhouse gas emissions. By cultivating microalgae in large-scale open ponds or closed photobioreactors, significant quantities of CO_2 can be absorbed and converted into biomass [43]. (2) Biofuel production. Microalgae can be used as a feedstock to produce biofuels like biodiesel and bioethanol. The lipids accumulated in microalgae can be extracted and processed into biodiesel, which can directly substitute for fossil fuels. Additionally, the carbohydrates present in microalgae may undergo fermentation to produce bioethanol [44]. (3) Food and feed production. Some species of microalgae have high nutritional value and can be used as a food source for humans or animals. Microalgae contain proteins, essential fatty acids, vitamins, and minerals, making them suitable for inclusion in various food and feed products [45]. (4) Wastewater treatment. Microalgae can remove nutrients, such as nitrogen and phosphorus, from wastewater through their growth and metabolic activities, purifying the water in the process [46]. (5) Carbon capture and utilization (CCU). Microalgal biomass can be used as a carbon source for bioplastics, biochemicals, and other valuable products, thereby reducing reliance on fossil fuel-derived raw materials [47]. These applications highlight the versatility of microalgae and their potential to contribute to carbon fixation, reduction, and sustainable resource utilization.

3. High-Value Carbon-Neutral Biofuel Production via the Torrefaction Process

3.1. An Overview of Torrefaction Technology

Torrefaction is a thermal treatment process that involves heating biomass, typically wood or agricultural residues, in the absence of oxygen [48]. The torrefaction process triggers the production of a dry and relatively stable solid fuel known as torrefied biomass or biochar. The main objective of torrefaction is to improve the properties of biomass, making it more suitable for energy conversion processes such as combustion, gasification, and co-firing with coal [49,50]. Some key aspects and characteristics of torrefaction technology are shown as follows:

(1) Temperature and residence time. In the torrefaction process, biomass is heated at temperatures ranging from 200 to 300 °C. The heating period is usually around 15–60 min, depending on the scale and design of the torrefaction reactor [51].

(2) Drying and volatile release. During torrefaction, moisture content and volatile compounds like methane, CO_2, and water vapor are removed from the biomass. This helps in increasing the energy density of the resulting torrefied biomass.

(3) Enhanced fuel properties. Torrefied biomass exhibits improved fuel characteristics compared to raw biomass. It has reduced moisture content, higher energy density, improved grindability, increased hydrophobicity (water resistance), and enhanced stability [52]. These improved properties make torrefied biomass easier to handle, transport, and store.

(4) Reduced emissions and environmental impact. The torrefaction process reduces the emission of greenhouse gases, such as CO_2 and methane, compared to the combustion of raw biomass [53]. Additionally, torrefied biomass possesses lower emissions of volatile organic compounds and other pollutants during combustion.

(5) Utilization in various energy conversion systems. Torrefied biomass can be used in existing coal-fired power plants, co-fired with coal, or utilized in dedicated biomass power plants and heating systems. It can also be processed further through gasification to produce synthesis gas (syngas) required to generate biofuels or other chemicals.

(6) Storage and transportation advantages. Torrefied biomass has improved storage properties due to its hydrophobic nature, making it resistant to moisture absorption. It can be stored for more extended periods without degradation [54]. The higher energy density of torrefied biomass allows for more efficient transportation over longer distances with reduced shipping costs.

(7) Carbon neutralization and sustainability. Using torrefied biomass as a renewable energy source contributes to carbon neutralization since the carbon released during combustion is balanced by the carbon absorbed by the feedstock during growth [55]. Additionally, torrefaction technology can utilize agricultural residues and forestry waste, promoting sustainable resource utilization and reducing environmental impacts.

Song et al. [56] selected maple sawdust as the feedstock and explored the coalification effect of the torrefaction process. They figured out that the main reaction mechanisms are the decomposition of unstable oxygenated functional groups, the degradation of celluloses, and the condensation of aromatic carbons. Jiang et al. [57] investigated the pelleting performance of torrefied microalga *Nannochloropsis Oceanica* residues, and indicated that the activation energies of pellets range from 5.83 to 77.71 kJ/mol. Mei et al. [58] explored the effect of temperature oscillation on the biomass torrefaction process, and pointed out that such an operation inhibited the intensity of the subsequent pyrolysis reaction. Overall, torrefaction technology is a promising approach for converting biomass into a more efficient and convenient form of solid fuel, and can be applied in various energy conversion systems while reducing emissions and enhancing sustainability.

3.2. The Carbon Neutralization Potential of Microalgal Torrefaction

Microalgal torrefaction is a thermal processing technique that involves the heating of microalgal biomass in the absence of oxygen to produce a solid, carbon-rich biochar [59]. This biochar can be used as a renewable energy source or as a soil amendment. In terms of carbon neutralization potential, microalgal torrefaction can sequester and store CO_2 from the atmosphere [60]. During microalgae growth, they absorb CO_2 through photosynthesis, converting it into organic compounds. Torrefaction of microalgae results in the formation of biochar containing the captured carbon, which effectively prevents its release back into the atmosphere. Furthermore, using microalgal biochar as a soil amendment can improve soil fertility, enhance nutrient retention, and promote carbon sequestration in soils [17]. This can contribute to reducing greenhouse gas emissions by storing carbon in the soil for extended periods. Microalgal torrefaction has the potential to be a carbon-neutral process as it allows for the sequestration and storage of CO_2, preventing its release into the atmosphere, and promoting carbon capture in soils [61]. However, the exact carbon neutralization potential would depend on various factors, such as the specific microalgae species used, the torrefaction process parameters, and the end-use applications of the resulting biochar. The results of elemental analysis and HHVs of various microalgae are listed in Table 2, and the systematic diagram of microalgal torrefaction process is shown in Figure 2.

Table 2. The results of elemental analysis and higher heating values (HHVs) of microalgae.

Microalgae Species	Elemental Analysis (wt %)				HHV (MJ/kg)	Reference
	C	H	N	O		
S. obliquus CNW-N	37.37	5.80	6.82	50.02	16.10	[62]
C. sp. JSC4	41.49	6.83	3.34	48.34	19.27	[63]
C. sp. JSC4 residue	48.06	7.62	3.81	40.51	16.91	[64]
C. *sorrokiniana* CY1	45.07	7.64	3.88	35.52	20.40	[65]
Chlorella vulgaris ESP-31 residue	47.78	7.85	4.14	40.23	17.90	[66]
Chlorella vulgaris ESP-31	53.01	8.67	3.26	35.05	22.02	[67,68]
Nannochloropsis Oceanica	53.98	8.18	8.42	29.42	21.02	[17]
Chlorella sp.	51.06	7.64	9.90	31.40	22.01	[17]
Chlorella vulgaris	45.66	5.90	9.05	31.95	18.77	[69]
Arthrospira platensis	36.49	6.12	7.89	49.51	12.66	[70]
spirulina platensis	45.70	7.71	11.26	25.69	20.46	[71]

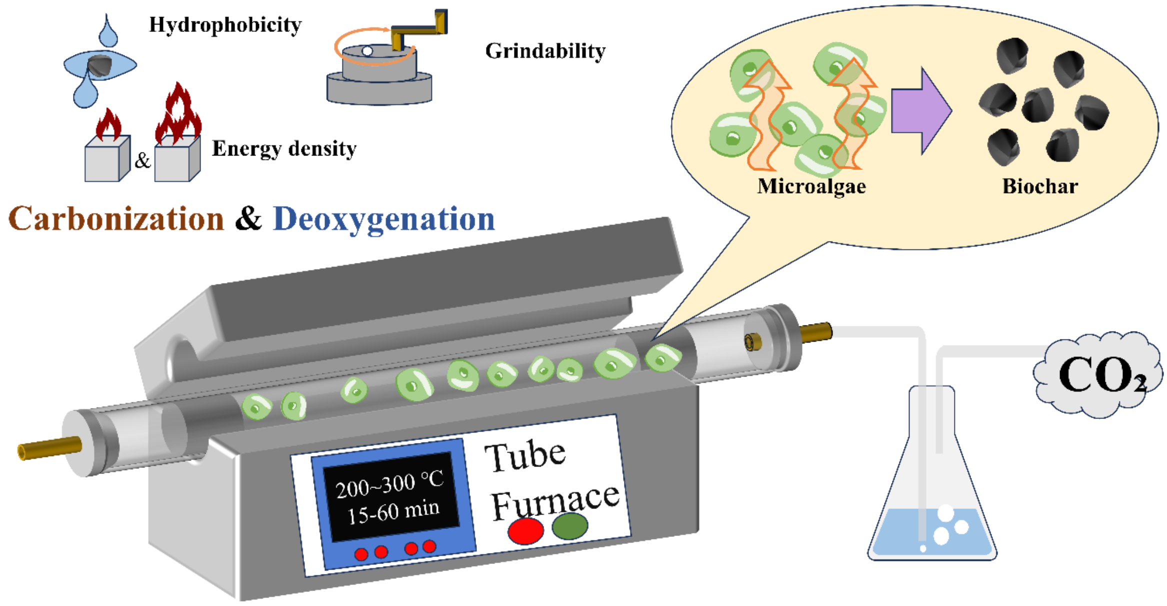

Figure 2. Systematic diagram of microalgal torrefaction process.

The carbon neutralization potential of microalgal torrefaction lies in its ability to sequester carbon and reduce greenhouse gas emissions [72]. The moisture and volatile components are removed from the microalgal torrefaction process, leaving behind a carbon-rich material. The torrefied microalgae can be used as a carbon sink by locking away carbon for an extended period. Furthermore, microalgal torrefaction produces a solid residue with a higher energy density than raw microalgae [73]. This torrefied microalgal biomass can be used as a renewable energy source, replacing fossil fuels and reducing CO_2 emissions from conventional energy production. In summary, microalgal torrefaction can contribute to carbon neutralization by sequestering carbon as torrefied microalgae and providing a renewable energy source that reduces greenhouse gas emissions [74]. However, further research are needed to optimize the process and assess its environmental and economic viability on a larger scale.

3.3. Practical Value and Development Prospect of Microalgal Carbon Neutral Biochar

Microalgal carbon neutral biochar, also known as microalgal biochar or microalgal-derived biochar, refers to the biochar produced from the torrefaction or pyrolysis of microalgae. It offers several practical values and has promising development prospects:

(1) Carbon sequestration. Microalgal carbon-neutral biochar acts as a long-term carbon sink by locking away carbon in a stable form. This helps to mitigate climate change by reducing greenhouse gas emissions [8].

(2) Soil improvement. Microalgal biochar improves soil fertility, water retention, and nutrient availability when applied to soils. It enhances soil structure, microbial activity, and nutrient cycling, improving crop growth and yield [75].
(3) Waste utilization. Microalgal carbon-neutral biochar can be produced from various types of microalgae, including those grown for wastewater treatment or CO_2 capture. This allows for converting waste biomass into a valuable product, contributing to waste management and resource recovery.
(4) Renewable energy production. The torrefaction or pyrolysis process to produce microalgal biochar generates biochar, bio-oil, and syngas [76]. These byproducts can be utilized as renewable energy sources, providing an alternative to fossil fuels and reducing greenhouse gas emissions.
(5) Sustainable agriculture. Applying microalgal biochar in agriculture can enhance soil health and reduce the need for chemical fertilizers. It promotes sustainable farming practices by minimizing nutrient leaching and improving soil resilience.
(6) Water quality improvement. Using microalgal carbon neutral biochar in water treatment systems can help remove pollutants, such as heavy metals and organic contaminants from wastewater [77]. This aids in water purification and contributes to environmental protection.

In terms of development prospects, microalgal carbon-neutral biochar holds significant potential. As research and technology advancements continue, there are opportunities to optimize production processes, develop innovative cultivation methods for microalgae, and explore the commercial viability of utilizing microalgal biochar in various industries [78,79]. However, additional research and pilot-scale studies are needed to fully understand its long-term effects, optimize production efficiency, and assess the economic viability of large-scale implementation. The profiles of application potential of microalgal carbon neutral biochar are shown in Figure 3.

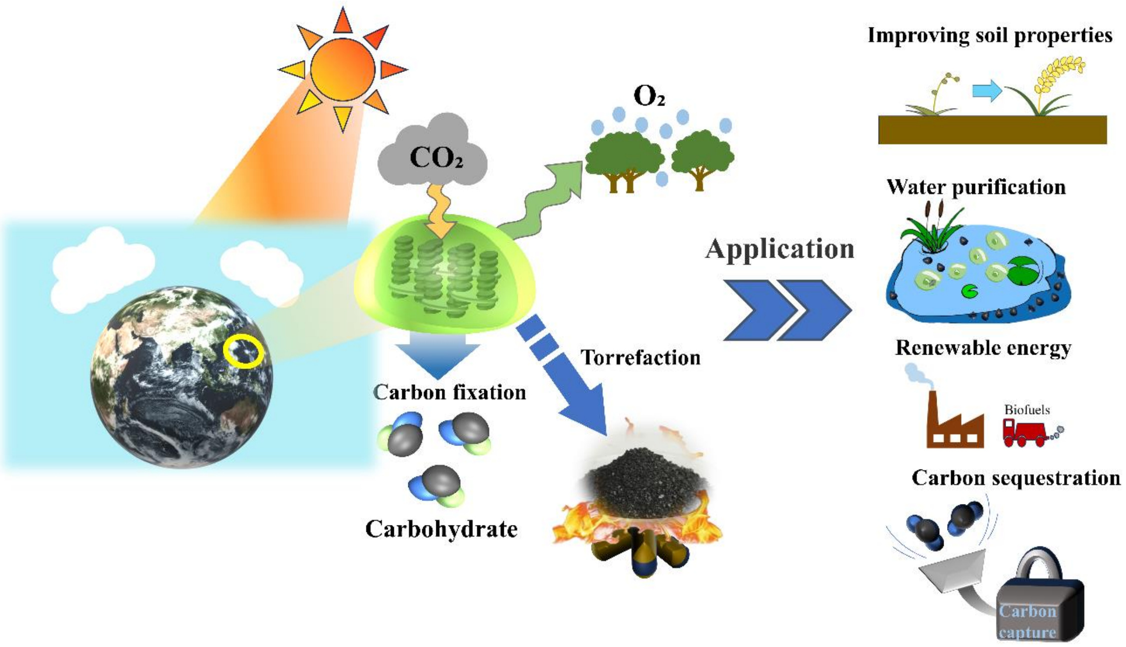

Figure 3. The profiles of application potential of microalgal carbon neutral biochar.

4. LCA for Environmental Impact Analysis of the Carbon Neutralization Process

4.1. A Brief Introduction of LCA in Microalgal Utilization

LCA is a methodology used to evaluate a product's or process's environmental impact throughout its entire life cycle, from raw material extraction to disposal. LCA provides a systematic and quantitative analysis of the environmental inputs and outputs associated with a particular system [3,80]. The application of LCA in microalgal utilization facilitates the assessment of the environmental performance of various microalgal-based products and processes. It considers factors such as resource consumption, energy use, emissions, and waste generation at each stage of the microalgal production and utilization chain [81].

LCA in microalgal utilization involves several key steps:

(1) Goal definition. Clearly defining the scope, objectives, and boundaries of the study. This includes specifying the purpose of the assessment, the functional unit being analyzed (e.g., per kilogram of microalgal biomass), and the system boundaries (e.g., from cultivation to end use) [82].
(2) Inventory analysis: Collecting data on the inputs (e.g., water, nutrients, energy) and outputs (e.g., biomass, CO_2 emissions) associated with each stage of the microalgal production and utilization process. This includes accounting for all relevant inputs and outputs, both direct and indirect [83].
(3) Impact assessment. Evaluating the environmental impacts of the system based on the inventory data. This involves categorizing the inventory data into impact categories such as greenhouse gas emissions, water consumption, land use, and toxicity. Different impact assessment methods can be used to quantify the impacts [84].
(4) Interpretation. Analyzing and interpreting the results to identify hotspots, areas of concern, and potential improvement opportunities. This step helps inform decision-making by considering the trade-offs and identifying strategies for reducing environmental impacts [85].

When evaluating the use of microalgae, LCA enables the comparison of various scenarios, technologies, and products to identify those with a lower environmental impact. It supports the development of sustainable microalgal-based applications, such as biofuels, feed additives, and wastewater treatment systems, by providing insights into the environmental implications throughout the life cycle [86,87]. The findings of LCA studies can guide researchers, policymakers, and industry stakeholders in making informed decisions to minimize the environmental footprint of microalgal utilization. The systematic diagram of microalgal carbon neutralization based on LCA is shown in Figure 4.

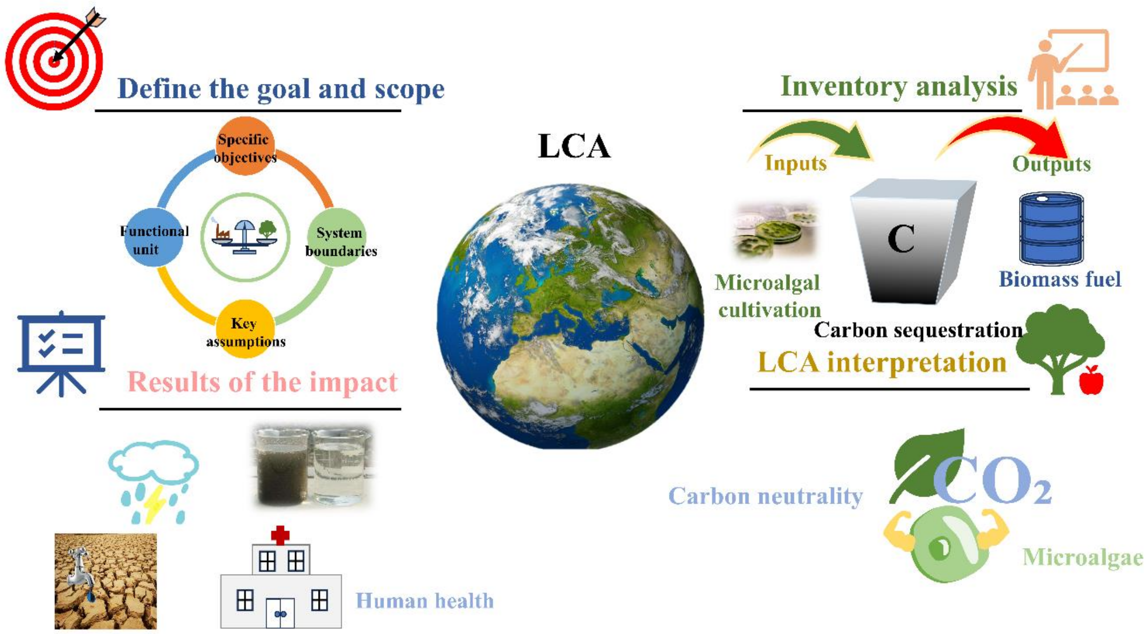

Figure 4. Systematic diagram of microalgal carbon neutralization based on LCA.

4.2. Environmental Impact Analysis of Microalgal Carbon Neutralization Process

The environmental impact analysis of the microalgal carbon neutralization process involves assessing the various environmental impacts associated with the production and use of microalgal carbon neutral products, such as biochar, biofuels, and other valuable byproducts [88]. The carbon footprint of the microalgal carbon neutralization process measures the total greenhouse gas emissions associated with the entire life cycle of the product. This includes emissions from cultivating microalgae, processing, transportation, and end-use applications [89]. The goal is to minimize or offset these emissions to achieve carbon neutralization. The energy consumption of the process is assessed to evaluate the efficiency and sustainability of microalgal carbon-neutral products [90]. It includes energy inputs required for cultivation, harvesting, processing, and conversion into desired products. The cultivation of microalgae requires land and water resources. Environmental analysis considers the potential impact on ecosystems, water availability, and land use change. Sustainable practices, such as using non-arable land or utilizing wastewater for cultivation, can mitigate these impacts [91,92].

Assessing the impact of microalgal cultivation on local biodiversity is crucial. Changes in land use, introduction of non-native species, and use of fertilizers or chemicals can potentially harm local ecosystems. Mitigation measures include the selection of native microalgal strains and minimizing chemicals use [93,94]. Proper management of waste generated during the process is essential to prevent pollution. This includes the responsible disposal or reuse of residual biomass, process byproducts, and wastewater. Recycling these materials can minimize environmental impacts. The process should be analyzed for potential water and air pollution. Nutrient-rich wastewater from microalgal cultivation can lead to eutrophication if not adequately managed [95]. Emissions from energy-intensive processes should also be controlled to avoid air pollution. Environmental impact assessment considers the economic and social aspects of the microalgal carbon neutralization process [96]. This includes assessing the feasibility of large-scale implementation, potential job creation, and overall benefits to local communities.

Life cycle assessment is commonly used to conduct a comprehensive environmental impact analysis. LCA evaluates the environmental impacts associated with each stage of the product’s life cycle, from raw material extraction to end-of-life disposal [97]. This helps identify hotspots and prioritize improvements to minimize the overall environmental footprint of microalgal carbon-neutral products. Therefore, comprehensive environmental impact assessments and LCA for the microalgal carbon neutralization process should be conducted to ensure its sustainability and minimize any potential negative environmental effects [98]. These assessments provide valuable information for decision-making, process optimization, and the development of sustainable microalgal-based technologies.

4.3. Analysis of Microalgal Carbon Neutralization Based on LCA

The LCA assessment of microalgal carbon neutralization involves evaluation of the environmental impacts associated with the entire life cycle of microalgal-based carbon sequestration processes. Notably, LCA provides a systematic approach to quantifying and assessing the potential environmental burdens and benefits of a product or process, from raw material extraction to end-of-life disposal [99]. The first step in the LCA is to define the goal and scope of the study. This involves identifying the specific objectives, functional units, system boundaries, and critical assumptions for the assessment of microalgal carbon neutralization. For inventory analysis, data on inputs (e.g., water, nutrients, energy) and outputs (e.g., biomass, waste, emissions) throughout the life cycle of microalgal-based carbon sequestration are collected and quantified [100]. This includes data on microalgal cultivation, harvesting, processing, transportation, and utilization. The collected inventory data are evaluated for its potential environmental effects using impact assessment methods. These methods consider various impact categories such as climate change, acidification, eutrophication, resource depletion, and human health effects. They help to understand the overall environmental performance of the microalgal carbon neutralization process [101].

The results of the impact assessment are interpreted to identify significant environmental hotspots and evaluate the sustainability of the microalgal carbon neutralization process. Sensitivity analysis and uncertainty analysis may also be conducted to assess the robustness of the results and address data limitations and uncertainties [102]. The findings of the LCA analysis provide valuable insights into the environmental performance of the microalgal carbon neutralization process. This information can identify improvement opportunities and guide the development of more sustainable practices, technologies, and strategies. Applying LCA to the microalgal carbon neutralization process makes it possible to identify areas where environmental impacts are the most significant and explore ways to optimize resource efficiency, reduce emissions, and minimize environmental footprints [103]. Moreover, LCA can assist in making informed decisions and developing sustainable microalgal-based carbon sequestration systems. LCA provides a holistic and quantitative approach to assess the environmental performance of microalgal carbon neutralization processes [104]. By identifying areas for improvement, LCA can assist decision-formulators to make informed choices toward more sustainable and environmentally friendly microalgal-based technologies.

5. Challenges and Prospects

5.1. Technical Difficulties of Microalgal Carbon Fixation and Torrefaction Process

The technical difficulties of microalgal carbon fixation and torrefaction processes are mainly reflected in the following aspects:

(1) Microalgal cultivation. Cultivating microalgae at a large scale can be challenging. Factors such as optimal nutrient supply, light intensity, temperature control, and minimizing contamination need to be

carefully managed. Maintaining high growth rates and biomass productivity while ensuring microalgal biomass's desired composition and quality is essential.

(2) Harvesting and dewatering. Efficiently separating microalgae from the culture medium and concentrating the biomass poses technical challenges. Traditional methods, such as centrifugation or filtration, can be energy-intensive and costly. Developing cost-effective and scalable harvesting and dewatering technologies is crucial to minimize energy consumption and maximize biomass recovery.

(3) Biomass drying. After harvesting, the moisture content in the microalgal biomass needs to be reduced for further processing. Drying microalgae can be energy-intensive due to the high moisture content. Developing energy-efficient drying methods, such as low-temperature or solar drying techniques, can help reduce energy requirements and associated costs.

(4) Torrefaction process optimization. Torrefaction is a thermal conversion process that involves heating biomass in the absence of oxygen to convert it into a more energy-dense, stable, and hydrophobic solid. Optimizing the torrefaction conditions, such as temperature, residence time, and heating rate, to maximize energy efficiency, carbon retention, and biochar quality is a technical challenge. Achieving consistent and uniform torrefaction across the biomass is also essential.

(5) Process integration and scale-up. Integrating microalgal cultivation, carbon fixation, and torrefaction processes into a complete and efficient system is complex. Scaling up processes from the laboratory to commercially viable levels presents technical challenges in reactor design, heat transfer, logistics, and economic viability. Addressing these challenges requires continuous research, development, and pilot-scale testing.

(6) Biomass quality and composition. The composition of microalgal biomass can vary depending on factors such as species, cultivation conditions, and harvesting methods. Variations in lipid content, protein composition, and nutrient levels can impact the torrefaction process and biochar properties. Therefore, understanding and controlling biomass quality and composition is critical for consistent and high-quality biochar production.

These technical challenges can be addressed through interdisciplinary research, involving collaborations between researchers and industry experts. Through continuous innovation, such efforts will optimize microalgal carbon fixation and torrefaction processes for maximum efficiency, environmental performance, and economic viability.

5.2. Prospects

The LCA of microalgal torrefaction for carbon neutralization has several prospects contributing to its potential as a sustainable solution. Here are some of the key prospects:

(1) Carbon neutralization. Microalgal torrefaction involves the conversion of microalgal biomass into a biochar-like product through thermal treatment. This process may lead to carbon-neutral or even carbon-negative outcomes. LCA can reveal greenhouse gas emissions and carbon sequestration potential throughout the entire life cycle, demonstrating the effectiveness of microalgal torrefaction in carbon neutralization.

(2) Renewable energy generation. The torrefied microalgal biomass obtained from the process can be used as solid biofuel for energy production. LCA can assess the environmental impacts associated with the combustion or gasification of torrefied biomass, including greenhouse gas emissions, air pollutants, and resource depletion. It facilitates the identification of the potential benefits and drawbacks of utilizing torrefied microalgal biomass as a renewable energy source.

(3) Waste valorization. Microalgae cultivation for torrefaction requires a substantial amount of biomass feedstock. LCA enables the evaluation of the environmental implications associated with producing and managing microalgal biomass, such as land use, water consumption, and nutrient inputs. By identifying the potential environmental burdens, LCA can aid in developing strategies to optimize resource utilization and minimize waste generation.

(4) Comparative analysis. LCA allows for a comparative analysis of microalgal torrefaction with other carbon neutralization and renewable energy technologies. By assessing the environmental performance of different options, decision-makers can make informed choices based on sustainability criteria. LCA provides insights into the strengths and weaknesses of microalgal torrefaction, helping to position it within the broader context of carbon neutralization strategies.

(5) Optimization and improvement. LCA serves to identify environmental hotspots and improvement opportunities within the microalgal torrefaction process. It facilitates the identification of specific areas

for optimization, including energy consumption, resource utilization efficiency, and emissions reduction. By incorporating the findings from LCA, researchers and engineers can make informed decisions to enhance the overall sustainability of microalgal torrefaction.

In summary, the benefits of applying LCA for microalgal torrefaction lie in its ability to assess the carbon neutralization potential, evaluate environmental impacts, facilitate waste valorization, enable comparative analysis, and support the optimization and improvement of the process. This comprehensive assessment can guide decision-making, promote sustainable practices, and contribute to developing a carbon-neutral future.

6. Conclusions

The life cycle assessment of microalgal torrefaction for carbon neutralization highlights the immense potential of this technology in achieving sustainable and environmentally friendly carbon neutralization. The review encompasses a comprehensive analysis of the environmental impacts associated with microalgal torrefaction throughout its entire life cycle. The LCA approach allows for a holistic evaluation of microalgal torrefaction, considering factors such as greenhouse gas emissions, resource consumption, waste generation, and renewable energy production. By quantifying these environmental indicators, LCA provides valuable insights into the process's strengths, weaknesses, and opportunities for improvement. The prospects identified through this review demonstrate the significant role that microalgal torrefaction can play in carbon neutralization efforts. Not only does it have the potential to achieve carbon-neutral or even carbon-negative outcomes, but it also offers opportunities for renewable energy generation and waste valorization. These aspects contribute to both mitigating climate change and fostering a circular economy.

Furthermore, the comparative analysis enabled by LCA allows decision-makers to evaluate microalgal torrefaction alongside other carbon neutralization technologies, facilitating informed choices based on sustainability criteria. This data-driven approach supports the formulation and execution of effective strategies for achieving carbon neutrality. Overall, this review highlights the critical role of integrating LCA into the development and application of microalgal torrefaction to promote carbon neutrality. Harnessing the full potential of this technology and utilizing LCA as an analytical tool will provide a strategy for achieving a sustainable future characterized by reduced greenhouse gas emissions, efficient resource utilization, and a thriving circular economy.

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