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Progress in the Application of Algae Plants in Building Carbon Capture Technology

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Abstract. Growing concerns over climate change and environmental pollution have increased interest in carbon capture technologies for the built environment. However, previous studies have mainly focused on conventional carbon capture materials such as carbonated concrete and engineered carbon capture systems., with relatively low attention paid to bio based carbon sequestration materials. This article takes microalgae, an emerging bio based carbon sequestration building material, as the starting point and conducts a comprehensive study on algae architecture through literature research. The main research objective of this article is to analyze the carbon sequestration principle of algae, summarize the forms of algae architecture, analyze the advantages of algae carbon capture, and explain the challenges it faces. This study found that algae have a much higher carbon capture efficiency than other organisms and are also easy to cultivate, which gives algae great potential in building carbon sequestration. There are two main forms of algae application in architecture, namely photobioreactor curtain walls and artificial trees. Among them, photobioreactor curtain walls mainly serve individual buildings, while artificial trees mainly serve the entire city. In addition, algae buildings have significant energy and environmental advantages compared to traditional buildings. However, as an emerging technology, algal architecture still faces many economic, technological, and social issues, such as high costs of experimentation and application, and inadequate regulatory measures. Future technological advances may help overcome these challenges and promote the wider application of algae-based carbon capture systems.

Keywords: Green Building, Carbon Capture, Microalgae

1. Introduction

1.1. Background

Climate change caused by increasing carbon dioxide emissions has become a major global concern. With the increasing population and demand for urban housing and the acceleration of urbanization, carbon emissions from the construction industry have become an important source of environmental pollution. In terms of energy consumption required for building operation, building operation often accounts for a substantial proportion of the total life-cycle energy consumption. of the total [1]; In terms of the production of main building materials, the carbon dioxide emitted by the production of

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cement and steel will cause considerable environmental pollution [2, 3]. In view of the above phenomenon, the cement and steel production industries have introduced many emission reduction measures for carbon dioxide emission reduction, but their effectiveness remains limited. (for example, the contribution of the emission reduction scheme of the cement industry to the achievement of the carbon dioxide emission reduction target is only 24%) [4, 5]. It can be seen that the traditional emission reduction measures are limited, so the there is an urgent need for more efficient carbon reduction technologies. At present, an algal carbon capture technology combining biological carbon sequestration mechanism and building has attracted scholars' attention. This technology combines microalgae with buildings to form algae buildings. Algae-based buildings utilize the biological characteristics of microalgae to capture atmospheric carbon dioxide, and capture carbon dioxide in the air through microalgae on the building facade, so as to achieve energy conservation and emission reduction [6]. At the same time, the strong adaptability of microalgae to the environment and the low demand for resources also reflect the advantages and potential of microalgae, and also improve the application possibility of algae buildings to a certain extent [7]. The BIQ House in Germany is widely recognized as one of the earliest successful examples of algae-based architecture [8, 9]. In today's society, green building has become the development trend of the times. The success of BIQ house shows that algae carbon sequestration technology has good development potential and prospects. Therefore, it is of far-reaching significance to explore algae carbon sequestration technology for the development of green building.

1.2. Research question

At present, algal building carbon capture technology has a certain research foundation, but its practical application effect, engineering feasibility, advantages and development limitations remain insufficiently evaluated in a comprehensive manner. This study will focus on the evaluation of the engineering application potential, challenges and limitations of algae building carbon capture technology.

1.3. Objectives of the study

First, summarize the major forms of algae applications in architecture. Second, analyze the carbon fixation mechanism of algae. Third, compare the advantages and limitations of carbon capture and storage by algae. Fourth, prospect the future development of algae in building carbon capture and storage technology.

1.4. Significance of the study

In the theoretical sense, this study can enrich the research on the combination of biotechnology and architecture, and it also contributes to integrating biomimetic principles into architectural design, which is the expression of the concept of "living design" [8]. In practice, this study can provide reference for the future low-carbon building design, provide new references for the development of green buildings, and promote the development of green buildings.

1.5. Overview of the paper structure

This paper first summarizes the existing literature research, starting from the current research status of building carbon sequestration technology, analyzes the existing materials (carbon dioxide absorption and biological) and traditional methods (concrete carbonation and photosynthesis) of

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building carbon sequestration, and then reflects the advantages of biological materials and photosynthetic carbon sequestration by comparing the differences between the two materials and the two methods, thereby highlighting the potential of algae as an emerging carbon sequestration material. With this topic as the core, this paper first analyzes the mechanism and principle of algae carbon sequestration, then analyzes the forms of algae applied to building carbon sequestration, then analyzes the advantages and limitations of algae applied to building carbon capture and storage, and finally looks forward to its future development.

2. Literature review

2.1. Overview of the existing research

2.1.1. Research status of building carbon sequestration technology

At present, with the continuous development and progress of building construction technology, more and more building materials can play a good role in carbon fixation in building construction. These materials capture and store carbon dioxide by chemical or biological means, and maximize their environmental optimization effect while maintaining the structure and aesthetic function of buildings [5].

2.1.1.1. Carbon dioxide absorbing material

Carbonated concrete is an effective carbon dioxide sequestration material.. Carbonated concrete stores carbon dioxide through the chemical reaction between carbon dioxide and its constituent materials to form stable calcium carbonate, which can not only improve the durability of materials, but also absorb a large amount of carbon dioxide [9, 10]. The current data show that carbonated concrete can store up to 15 kg of carbon dioxide per cubic meter, and showing considerable carbon reduction potential [5]. Carbonated concrete can absorb up to one fifth of its own weight of carbon dioxide, which is an excellent sustainable material for building construction [5]. At present, in some cities in North America, carbonated concrete has been used in urban infrastructure, and has achieved good social and environmental benefits [5]. Overall, carbonated concrete has been widely applied as a carbon capture material in the construction sector.

2.1.1.2. Biological carbon sequestration materials

Algae is a new biological carbon fixation material suitable for building construction, which is still in the early stage of development [8]. The building facade based on algae can integrate photosynthetic microorganisms outside the building, which can not only produce biomass as energy or materials for buildings, but also capture carbon dioxide in the air to protect the environment [5]. Current research has found that the energy consumption of buildings with microalgae curtain walls can be reduced to two-thirds of ordinary buildings, and the power consumption can be reduced to 90% of ordinary buildings, so as to achieve better temperature control [8]. It can be seen that algae, as a new biological carbon capture material, also has the carbon capture effect no less than that of carbonated concrete, but as an emerging technology, the technical maturity of algae carbon capture is less than that of carbonated concrete.

2.1.1.3. Analysis and comparison of carbon capture capacity of two materials

Carbonated concrete is indeed a mature carbon capture material suitable for construction, with strong carbon capture ability, but the carbon produced by the production of carbonated concrete cannot be ignored. The production of carbonated concrete requires a large amount of cement, and the production of cement is a high energy consuming industry that is highly dependent on carbon based fuel and reductant. The carbon dioxide emissions caused by it account for a large proportion of the total global emissions, up to 7% [2]. Therefore, from the perspective of "production of carbonated concrete" and "carbon capture capacity of carbonated concrete products", the actual net carbon capture of carbonated concrete will be reduced by the amount of carbon released by its production, and its net carbon capture effect will be greatly reduced. The amount of carbon captured by algae can not only compete with that of carbonated concrete, but also the energy and carbon released by algae are much lower than that of carbonated concrete. The cultivation of algae can not only recycle wastewater, but also do not need herbicides or pesticides [7]. This means that the negative environmental impact caused by the production of algae is lower than that of the production of carbonated concrete, and the net carbon capture of algae may be higher than that of traditional carbonated concrete when the carbon capture capacity is equivalent. Under the background that the concept of green building has become a social trend, Algae-based carbon capture demonstrates promising potential owing to its lower life-cycle environmental impact.

2.1.2. Research progress of algae carbon sequestration

At present, there are relatively mature cases of algae carbon sequestration buildings, such as BIQ house in Germany. BIQ house is the first building with algae facade system. The current research data show that the thermal energy conversion rate of the system is 38%, the bioenergy conversion rate is 10%, and the energy utilization rate is relatively good. The energy demand of the whole building is reduced to half of the original, and it is expected to achieve all aspects of energy self-sufficiency in the future [8, 9]. As the pioneer of algae building, BIQ house can play a good role as a model. Its success has greatly boosted the morale of the development of algae buildings, and provided a valuable reference for the construction of subsequent algae buildings.

2.2. Literature gap

The existing research focuses on the application of algae bioenergy or sewage treatment, while the systematic evaluation of the combination of algae and building space is still less, and the measures on how to deal with the challenges faced by the development of algae buildings are relatively lacking. With the application of microalgae in architecture becoming a new potential field, there are still several gaps and challenges to be explored in order to achieve its high-quality development, mainly including:

(1) Its practical application effect

(2) Its engineering feasibility

(3) Various restrictions on its development

By solving these gaps, microalgae can better play the role of carbon fixation and energy conservation and emission reduction in buildings.

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3. Methodology

The primary research methodology employed in this study is literature review. By conducting searches in databases such as Google Scholar, Web of Science, and CNKI for keywords related to algal architecture, including algae façade, microalgae building, carbon capture, and green building, this study systematically reviewed eligible journal articles, books, and reports., monographs, and academic reports. Additionally, it comprehensively reviewed and analyzed existing research findings, theoretical foundations, and development histories pertaining to algal architecture. This study delves into the potential and advantages of carbon capture inherent in algae, as well as the difficulties and challenges faced by algal architecture, exploring the connections and contexts between them. This approach provides a comprehensive understanding of current research progress and remaining challenges.

4. Results

4.1. Summary of building carbon sequestration technology

From the perspective of process, building carbon capture is mainly divided into two steps, carbon capture and carbon storage. Carbon capture in buildings, in short, is to "capture" industrial emissions or carbon dioxide in the atmosphere through biological processes or artificial technologies to mitigate its impact on climate change [10]. The carbon storage of buildings, in short, is to "store" the captured carbon dioxide in various forms for a long time to prevent them from escaping back to the atmosphere [10]. From the perspective of method, the main methods of building carbon sequestration are concrete carbonation and photosynthesis. At present, concrete carbonation has been well known as a mature technology, and photosynthesis is a natural carbon capture mechanism of plants, which is closely related to bio-based building materials. Photosynthesis can make plants use solar energy efficiently. With the help of solar energy and a series of chemical reactions, carbon dioxide in the air can be transformed into biomass for their own growth, which plays a role of carbon capture and storage in disguised form [10]. At present, algae and other new carbon fixation materials based on biological photosynthesis have shown great potential in building carbon capture.

4.2. Algal carbon sequestration mechanism

4.2.1. Specific principle of algae carbon fixation

The core of algal carbon sequestration mechanism is its own bicarbonate pump. Thanks to the bicarbonate pump, algae can concentrate bicarbonate in their own cells. Then, the concentrated bicarbonate will be dehydrated to produce carbon dioxide, which will be recycled and captured by Calvin [6]. The overall carbon fixation process can be summarized as follows: algae first "pump" bicarbonate into cells to save it, and then try to turn it into carbon dioxide. Finally, this carbon dioxide will be fixed in cells through the Calvin cycle (Fig.1). Fig 1 describes the carbon sequestration steps of microalgae.

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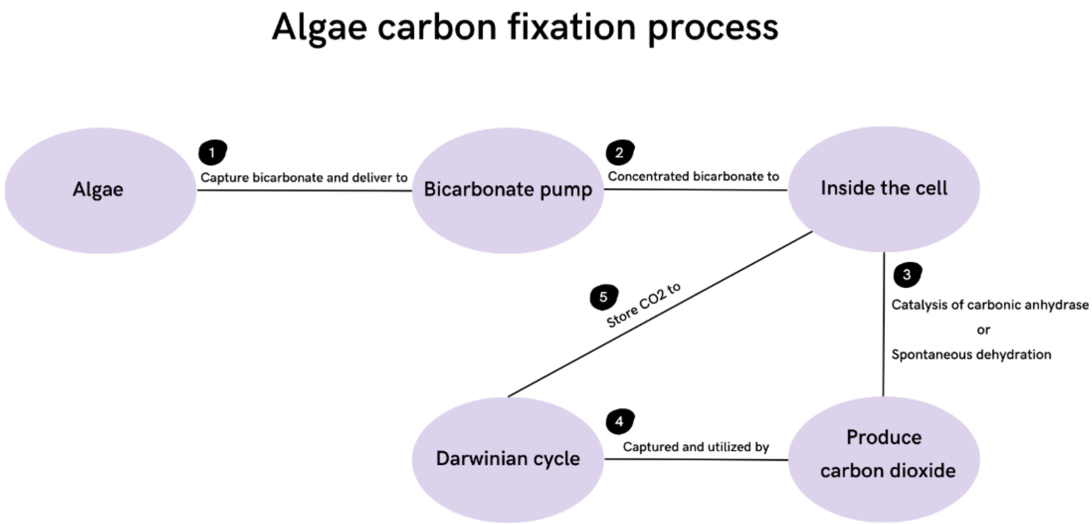

Figure 1. Steps of carbon dioxide (CO2) fixation by algae

4.2.2. Comparison of algae carbon sequestration efficiency

Current research has found that algae are one of the most productive biological systems, with carbon capture efficiency far exceeding that of other organisms. At the same time, they can efficiently capture carbon while creating biomass that is beneficial for environmental development. In general, the photosynthetic efficiency of microalgae ranges from 10% to 20% or even higher, while in contrast, the global average photosynthetic efficiency of most terrestrial plants with grades higher than microalgae is only 1% to 2% [7]. Moreover, in the optimal state of an open pond, algae can capture up to 99% of carbon dioxide [6]. These findings suggest that microalgae possess superior carbon capture capacity compared with many terrestrial plants, microalgae have a significant advantage in carbon capture capacity. However, there are differences in carbon capture efficiency among different types of microalgae. In general, Phaeodactylum tricornatum is the microalgae species with the highest carbon capture efficiency, reaching up to 21.6%. In comparison, the carbon capture efficiency of Synechococcus sp. is the least significant, only about 2-4% [7]. Therefore, selecting the appropriate species of algae has a significant impact on the carbon sequestration efficiency of algae buildings.

4.3. Forms of algae applied to buildings

4.3.1. Photobioreactor curtain wall

4.3.1.1. Overview of photobioreactor curtain wall

Photobioreactor curtain wall is one of the main forms of microalgae application in buildings. Photobioreactor (PBR) is a type of microalgae growth system mainly made of glass or polyethylene of different densities, which can be perfectly integrated into existing building exterior design [11, 12]. Thanks to the extremely small growth space requirements of microalgae and their strong adaptability, photobioreactors can perfectly adapt to various types of building infrastructure [11]. At

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present, buildings equipped with photobioreactor curtain walls have demonstrated impressive energy-saving and emission reduction potential in multiple regions around the world, such as New South Wales in Australia [13].

4.3.1.2. Types and working principles of photobioreactors (curtain walls)

At present, there are four different types of photobioreactors: tubular, flat plate, trough, and hybrid. Among them, tubular photobioreactors are further divided into vertical and horizontal types [12]. Although the working mode of the photobioreactor curtain wall varies depending on the type of photobioreactor, its overall working steps can be summarized into five steps: adjusting and optimizing light, mixing and circulating nutrient solution, exchanging gas, controlling the environment (temperature and pH value, etc.), and harvesting (Fig.2). Taking flat plate photobioreactor and horizontal tube photobioreactor as examples. The flat plate photobioreactor is used to cultivate microalgae in a flat rectangular cavity made of transparent material. Nutrient mixing is achieved through aeration, and the high-efficiency utilization of light relies on its extremely high surface area to volume ratio, thereby achieving the goal of cultivating high-quality algae in buildings [12]. The horizontal tubular photobioreactor uses a pump driven liquid circulation system consisting of a circulation pump to receive light in a horizontal or inclined transparent pipeline, and relies on an external degassing device to maintain gas and nutrient balance in the system, thereby efficiently cultivating microalgae [12]. In summary, the photobioreactor curtain wall achieves the goal of energy conservation, emission reduction, and carbon reduction by cultivating high-quality algae on the surface or inside of buildings through different types of photobioreactors. Fig 2 describes the working steps of PBR

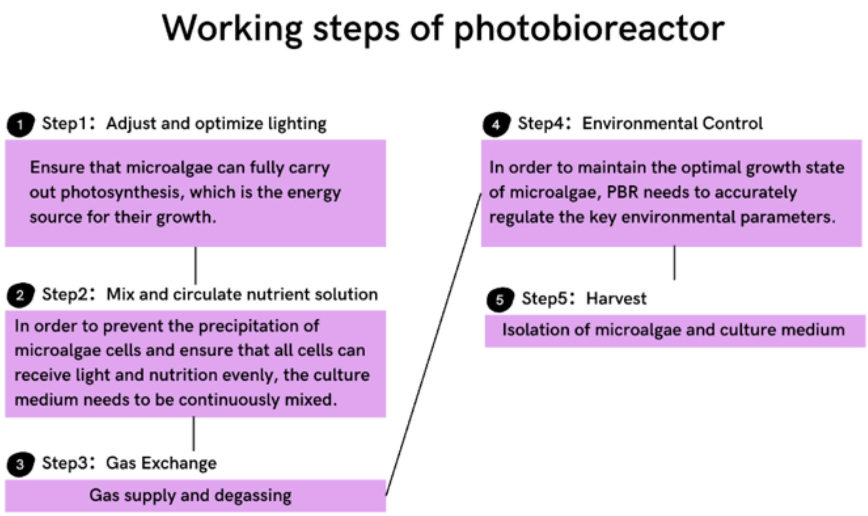

Figure 2. Working steps of photobioreactor

4.3.1.3. The impact of photobioreactor curtain wall

Previous studies have shown that the impacts of photobioreactor curtain walls can be summarized in three main aspects. Firstly, from the perspective of building energy consumption, photobioreactors help improve the circulation and utilization efficiency of resources within buildings, including water and energy [13]. Secondly, from the perspective of building use, photobioreactor curtain walls, as a

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dynamic building façade system, can reduce building carbon emissions while improving indoor environmental quality and occupant comfort, and can also produce biomass for further utilization [12]. Thirdly, from the perspective of architectural aesthetics, photobioreactor curtain walls represent an innovative façade design approach and provide a new design language for contemporary architecture [11].

4.3.2. Artificial trees

4.3.2.1. Overview of artificial trees

Artificial trees represent another application of microalgae in architecture. They are an innovative urban infrastructure concept that integrates microalgae cultivation systems into urban furniture, aiming to achieve carbon dioxide capture, biomass production, and urban environmental improvement by mimicking the structure and functions of natural trees [11]. At present, the prototype of the project has been installed in the city of Alcocon in the autonomous region of Madrid and has achieved good environmental benefits [11].

4.3.2.2. The working principle of artificial trees

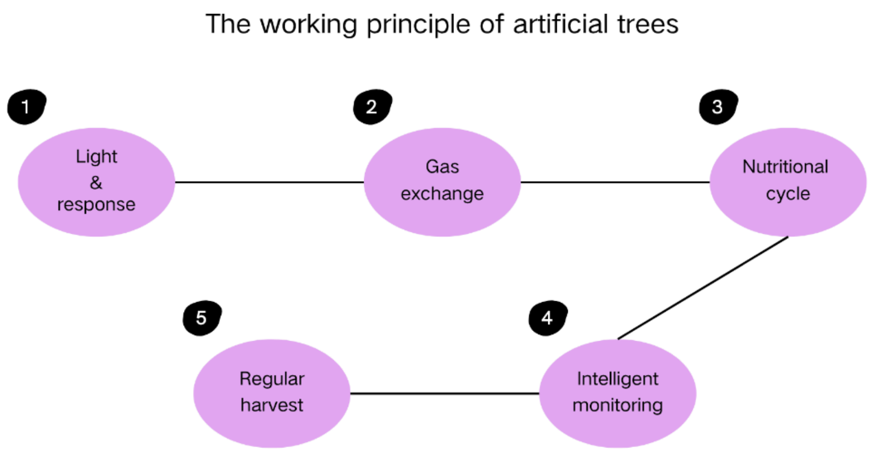

Figure 3. Artificial tree workflow

The working steps of artificial trees can be summarized into five stages: light and reaction, gas exchange, nutrient cycling, intelligent monitoring, and regular harvesting (Fig.3). Firstly, the artificial tree receives solar energy through 9 huge "leaves", which are used for photosynthesis by microalgae inside the device [11]. As photosynthesis progresses, the concentration of carbon dioxide in water will decrease. At this point, the bubble column located inside the "tree trunk" will inject air rich in carbon dioxide into the circulating water to supplement the carbon source needed by microalgae [11]. Meanwhile, a hydraulic pump drives the culture medium containing microalgae to continuously circulate throughout the system, ensuring that all microalgae receive uniform light and nutrients [11]. During this period, a dedicated remote monitoring system will monitor key parameters of the cultivation environment in real-time through multiple sensors, ensuring that

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microalgae grow under optimal conditions. After the microalgae grow and mature, the system will conduct regular harvesting [11]. Fig 3 describes the workflow of artificial trees

4.3.2.3. The impact of artificial trees

Through research, it has been found that the impact of artificial trees mainly includes the following three points. Firstly, from the perspective of environmental impact, the application of artificial trees in cities can largely capture carbon dioxide in urban air, while sharing the carbon capture pressure of traditional trees in cities and providing a larger shading area [11]. Secondly, from the perspective of social impact, artificial trees, as interactive areas in cities, integrate multiple functions such as seating, lighting, and educational displays, greatly enhancing the experience of urban users [11]. Thirdly, from the perspective of aesthetics and integration, the appearance design of artificial trees is very innovative, which can enhance the city's image to a certain extent. At the same time, it adopts a modular structure, which is easy to expand and maintain [11].

4.3.3. Comparison of two application forms

Photobioreactor Curtain Walls and artificial trees are both forms of algae application in architecture, which can utilize microalgae to play a good role in carbon capture and contribute to the development of green buildings. But they also have some differences. From the perspective of application scale, photobioreactor curtain walls focus on the application in individual buildings, improving local environmental quality by optimizing individual buildings. Artificial trees, on the other hand, are more like infrastructure in a city, serving the entire city rather than a specific building. From the perspective of application, photobioreactor curtain walls must be attached to the building itself in order to function effectively, while artificial trees can exist and operate independently in the city, detached from the building.

4.4. Advantages of algae technology

4.4.1. Biological characteristics advantages of algae

Firstly, microalgae are common photosynthetic microorganisms that mainly inhabit aquatic environments and are widely distributed throughout the world. They can not only adapt to a wide range of environmental conditions, but also survive in different climatic zones [7]. Meanwhile, microalgae have a short growth cycle, a rapid growth rate, and can utilize large amounts of carbon dioxide to produce various types of biomass [7]. This means that, compared with many other photosynthetic organisms and higher plants, microalgae can fix more carbon dioxide per unit time [7]. Secondly, microalgae have high carbon sequestration efficiency. They are considered one of the most efficient biological systems for carbon capture [6]. Under optimal conditions, microalgae can capture up to 90% of carbon dioxide [6]. Meanwhile, the carbon sequestration efficiency of microalgae is closely related to the concentration of carbon dioxide in the growth environment: higher carbon dioxide concentrations generally promote microalgal growth and enhance their carbon capture capacity [7]. Thirdly, microalgae have strong salt tolerance, allowing them to be cultivated using both freshwater and saline water resources [7]. Meanwhile, the cultivation and maintenance of microalgae can make use of recycled water. Microalgae can also utilize nutrients such as nitrogen (N) and phosphorus (P) from various wastewater sources, including urban sewage, agricultural

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runoff, and industrial wastewater [7]. This not only supplies nutrients for microalgal growth but also contributes to wastewater recycling and purification.

4.4.2. Energy and energy consumption advantages of algae façade

Buildings with microalgae facades can generate clean energy while reducing harmful gas emissions, so they typically have good energy and energy efficiency [8]. Thanks to this, the energy consumption and operating costs of such buildings will be greatly reduced, which means they have stronger energy tax reduction and profitability. Research has found that buildings with PBR facades can reduce building energy consumption by over one-third, including but not limited to saving over 10% of electricity consumption [8]. Meanwhile, thanks to the PBR system, the energy consumption demand of buildings has been successfully reduced by half. If the PBR system can be combined with solar energy systems in the future, buildings may achieve energy self-sufficiency [9].

In addition, at the level of small communities, a community equipped with a microalgae integrated system can achieve self-sufficiency in hydropower resources and self treatment of sewage to a certain extent while capturing carbon dioxide and nuclear pollutants in the air [8]. At the level of large cities, the integrated use of algae building facades can not only clean the city's air and improve air quality, but also enhance the city's image and aesthetics [9].

4.4.3. Environmental advantages of algae façade

Through research, it is found that the algae facade of the building not only contributes to outdoor shading, but also prevents excessive light from hitting the interior of the building [8]. In summer, this can not only provide a shady area for pedestrians outside the building, but also improve the comfort and satisfaction of users inside the building, killing two birds with one stone. In addition, buildings with microalgae boxes can adjust the light and temperature in the building through the efficient photosynthesis performance of microalgae, and improve the indoor air quality while reducing carbon emissions [8]. At the same time, algae facade as a dynamic building shell can meet the above conditions and produce biofuels and biomass for other purposes [13]. This undoubtedly alleviates the pressure of energy consumption on the environment to a great extent.

4.5. Challenges

4.5.1. Stringent requirements for algae species

Current studies indicate that selecting appropriate algal strains is the key to achieving effective carbon capture and storage in algal façades [7]. The ideal algal strain for building façades should meet the following requirements: First, it should have high tolerance to carbon dioxide and strong carbon fixation capacity; Second, it should be able to adapt to daily temperature fluctuations and seasonal climate changes while maintaining low nutrient requirements; Third, it should have a short growth cycle, high photosynthetic efficiency, and the ability to produce valuable by-products [7]. However, no algal strain has yet been reported to satisfy all of the above requirements simultaneously [7].

4.5.2. Technical, economic and social issues

Algal facade technology is still in its early stages and needs to address many economic, technological, environmental, social, and regulatory issues [8].

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From an economic perspective, the cost of microalgae systems is a major obstacle to their widespread adoption. In terms of maintenance, the upkeep of algae facades requires intensive labor and specialized equipment, and the procurement and maintenance of these equipment require significant financial and labor costs [9]. In terms of usage costs, microalgae eco-friendly building facades, as an emerging technology, mean that the initial cost of implementation or application is very high: research has found that the cost of a bioreactor system alone is as high as about $2500 per square meter [14, 15]. In terms of water cost, algae require irrigation from water sources, which means that how to avoid water waste is an important issue to be addressed [9].

In terms of technology, how to implement this emerging technology in reality is also a major challenge. Since 2013, designers have only designed and built one microalgae building in Hamburg, Germany, and the universality of implementation cases still needs to be improved [15]. Therefore, further research and exploration are needed on whether microalgae architecture is universally applicable in different regions with different climates.

From both a technical and economic perspective, the exploration of the applicability of microalgae architecture implies that society may need to invest significant amounts of money and resources in conducting long-term experiments around the world. This will invisibly increase the cost and economic pressure of popularizing and implementing algae architecture.

In terms of the environment, if microalgae that are not suitable for the local environment are used in buildings, potential problems such as toxins and odors may arise, which can have a significant negative impact on the environment [15].

In terms of society and regulation, emerging algae buildings may not be compatible with existing building codes and regulations [9]. This means that corresponding laws, regulations, and guidance standards need to be re formulated to regulate the development of algae buildings. Meanwhile, in terms of architectural aesthetics and socio-cultural differences, buildings with algae facades may make it difficult for some people and special cultural groups to accept [9]. This means that when applying algae architecture, cultural differences should be valued and different cultures from different regions of the world should be respected, so as to promote the popularization of algae architecture.

From the perspective of environmental and social regulation, if we want to minimize the adverse effects of using inappropriate microalgae in buildings on the local environment, then society needs to formulate new laws, regulations, and supervisory rules to regulate the development of algae buildings. This means that the consideration of environmental factors in algae buildings may inadvertently impose a burden on social regulation.

5. Conclusion

5.1. Summary of key findings

Algae have considerable potential for biological carbon sequestration, and algae-based buildings demonstrate significant advantages in energy conservation and carbon reduction. However, owing to challenges such as high implementation costs and technological barriers, algae-based carbon capture is unlikely to replace conventional CCS technologies in the near future, but it has strong potential to serve as a complementary low-carbon solution for sustainable buildings..

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5.2. Comparison with previous studies

Previous research on building carbon sequestration technology has mainly focused on traditional carbon sequestration building materials, with relatively low attention paid to emerging bio based carbon sequestration materials. In terms of research on bio based carbon sequestration building materials, previous studies have been detailed and thorough on the potential and advantages of algae, but there is relatively little research on their actual application effects, engineering feasibility, and limitations.

Compared with previous studies, this article summarizes the potential and advantages of algae, and analyzes the forms and working principles of algae application in architecture, comparing the differences in different application forms and their impact on society. At the same time, this study also analyzed the limitations and challenges faced by the development of algae architecture from multiple perspectives (economic, technological, social, etc.), providing a comprehensive analysis of the advantages and disadvantages of algae architecture.

5.3. Implications of the findings

From a theoretical perspective, this study provides a systematic review of algae architecture and offers a reference for integrating biological carbon sequestration technologies into green building design. From an engineering perspective, the analysis of the working principles and application potential of algae architecture may provide useful guidance for future engineering practice. Furthermore, the challenges identified in this review provide possible directions for future research and may contribute to the continuous improvement and wider application of algae architecture.

5.4. Limitations of the study

This study has the following limitations.

First, the current cases of algae building are limited. Although the BIQ house in Hamburg, Germany, is a successful attempt of algae building, it does not mean that the algae building is perfect. The advantages and limitations of algal architecture need to be further studied.

Second, the influence of different climatic conditions on algae growth and building performance has not been fully understood. Since climate can significantly affect the cultivation and application of microalgae, future studies should investigate region-specific environmental conditions and develop algae species suitable for different climatic zones.

Third, it is difficult to compare the carbon sequestration of algae uniformly. The carbon sequestration capacity of algae is affected by uncontrollable factors such as growth environment, weather, temperature, humidity, and light in practical applications, resulting in different experimental conditions. This can lead to significant changes in their carbon sequestration capacity, making it difficult to measure uniformly. Different studies have different testing conditions, so the comparability of data is limited.

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