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The Development of CO2 Capture and Storage Technology in the Field of Architecture and its Challenges and Solutions

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Abstract. The architecture industry constituted a significant source of carbon emissions, underscoring the urgent need for energy efficiency and emission reduction strategies. In this context, carbon capture and storage (CCS) technologies within the architectural domain emerged as critical research areas. This paper systematically classified and summarized various CCS technologies based on specific sub-fields of architecture, drawing on an extensive review of existing literature. Notably, urban design and planning, building materials, and landscape architecture presented numerous promising carbon sequestration technologies. In urban planning, this paper emphasized the development of supportive planning and decision-making tools aimed at enhancing carbon sequestration efficacy. In the realm of building materials, innovative approaches incorporated CO2 absorption into materials, facilitating permanent carbon sequestration. Meanwhile, landscape architecture focused on refining and optimizing traditional techniques, integrating novel technologies to improve outcomes. The status of these technologies varied considerably, with some having progressed to commercial viability. However, challenges persisted in their widespread adoption. To advance the development of these technologies, this paper highlighted the importance of addressing inherent technical deficiencies and evaluating economic viability, thereby enhancing the dissemination and implementation of carbon sequestration methods within the architecture sector.

Keywords: Carbon Capture and Storage; Urban Planning; Building Materials.

1. Introduction

With the occurrence of global warming and climate change, the treatment of greenhouse gases has been attached great importance. Reducing direct emissions of carbon dioxide on the one hand, and capturing and storing the generated carbon dioxide on the other has become the important research interests since CO_2 proved to be the main greenhouse gas. Cement, steel, etc. are all important sources of global CO_2 emissions. For example, the production of cement, an important building material, accounts for 7% of total CO_2 emissions [1]. The construction industry is therefore also an important source of carbon emissions, as well as carbon emissions from the use of buildings. There are many aspects of the entire life cycle of buildings that produce CO_2, not just the production of cement. Effectively reducing CO_2 emissions in the construction industry will make a significant contribution to reducing total carbon emissions.

Kinnunen et al. reviewed the carbon sequestration capacity of urban residential environments, pointing out that residential green spaces and buildings provide carbon capture and storage, which have a positive impact on the climate, but have received less attention in the scientific literature. It is concluded that the carbon pools of residential vegetation, soil, and wood structures have the greatest potential, and biochar and other bio-based building materials are important fields for future development [2]. Hanif et al. reviewed the recent developments in CO_2 capture and storage in the construction industry and its relation to global warming. One part is CO_2 capture in the cement production process. In addition, the emerging methods of carbon capture and storage, as well as some commercial technologies that have been put into production by some companies, are introduced and evaluated for their carbon sequestration benefits, and suggestions for the development of these technologies are made [3]. Kaliyavaradhan et al. summarized the application of construction and demolition waste in carbon sequestration and various active carbonation technologies, including recycling concrete aggregates and concrete waste, and focused future research on the applicability of a wider variety of concrete and the application of this technology in construction [4]. Shang et al. reviewed the low-carbon technologies, including carbon capture and storage technology, that have been used to achieve the goal of urban carbon neutrality in the past decade (2013-2022). It is concluded that more than 80% of the technologies are to collect CO_2 from the air, but the storage speed and efficiency are generally not ideal at present, which should be addressed [5].

In summary, previous research has extensively covered systematic solutions to reduce the total carbon emissions of buildings in life cycle assessment, as well as the technology and practical application of carbon capture and storage in various life cycles of buildings, which have been less studied. The difference in research progress between these indicates that there is a lack of research on reducing net carbon emissions in life cycle assessment of buildings, which is formed by reducing total carbon emissions and increasing carbon capture and storage. There are also few search results on the combination of carbon capture and storage with architecture.

This study had positive significance for constructing a full-process approach for carbon capture and storage in architecture, which in turn has positive significance for reducing net carbon emissions in the life cycle assessment of buildings. Against the backdrop of the construction industry becoming an important source of carbon emissions, it is beneficial for the development of low-carbon buildings and green buildings, and is conducive to achieving the goals of carbon peak and carbon neutrality.

This study focused on summarizing the technical principles and application progress of building carbon capture and storage, aiming to analyze its advantages and disadvantages as well as its potential contribution, explore its development trend, and show its uniqueness, technical difficulties, economic obstacles, and future prospects. It takes green building materials, architecture landscape carbon sinks, zero-carbon urban planning, and other aspects as options to provide suggestions for achieving the carbon peaking and carbon neutrality goals.

2. Technology and Research Status of Carbon Capture and Storage in Architecture Field

2.1. Urban Planning and Spatial Planning

(1) In urban planning, researchers use multi-objective programming (MOP) algorithms to optimize the structure of land, maximize carbon sink benefits, and analyze the trade-off between economic and ecological benefits. Based on the results, spatial allocation is carried out through patch-level land use simulation (PLUS) to determine the growth boundary of the city [6]. Effectively incorporate carbon sequestration into urban planning strategies to achieve sustainable low-carbon urban growth.

(2) Other researchers have conducted research on the carbon sink effect of urban underground space, quantitatively evaluated the ecological carbon sink potential of using urban underground space, and designed planting strategies for urban blue-green spaces (BGS) based on this, establishing a carbon sink benefit evaluation method based on land use carbon emission models [7].

(3) Regarding urban planning strategies, some researchers have proposed the analytic network process (ANP), which involves analyzing the mutual influence of various factors and assigning weights to each factor. Using multiple indicators, including urban structure improvement, urban infrastructure improvement, and community development, to evaluate various low-carbon strategies and derive a project's overall score, it can help urban planners make decisions [8].

2.2. Carbon Capture and Storage Technology Related to Construction Materials

(1) The waste materials generated during the production of concrete can be carbonated. In addition, carbonation of cement-based materials used as building structures is also an important way to capture carbon, while improving the early strength of cement, which is superior to traditional hydration curing. At present, the recycling rate of construction waste in developing countries is relatively low.

Recycling construction and demolition (C&D) waste into recycled aggregates (RA) is also an important method for building waste disposal and carbon capture. During the carbonization process of recycled aggregates, their compressive strength will gradually increase, allowing building materials to gradually reach the level of new aggregate concrete.

(2) There are many methods for CO_2 capture and storage in building materials that have been put into commercial use. The accelerated carbonation technology (ACT) of Carbon8 Systems Ltd. can be combined with various industrial wastes (thermal wastes, waste energy, steel slag, etc. from cement production sites) to produce artificial limestone and recycled aggregates. According to this technology, 20% of the available waste in Europe can permanently absorb 1 million tons of CO_2. CarbonCure uses developed a technology that injects carbon dioxide into concrete mixtures to accelerate the initial and final set during the curing process, as well as increase its strength and other indicators. Blueplanet uses a method of manufacturing artificial fine and coarse aggregates through mineral carbonation, which absorbs a large amount of carbon dioxide and makes the entire structure carbon-negative. Carbstone adds carbon dioxide from flue gas to steel slag to form blocks, which also have carbon-negative properties.

2.3. Carbon Capture and Storage Technology Related to Landscape Architecture

There is no technical threshold for landscape design, and research in this area mainly focuses on how to optimize the carbon sink benefits of the landscape system. The main research approach is to compare the carbon sinks of different landscape schemes to obtain a better solution. Numerous sophisticated methods have been developed for assessing the carbon sequestration benefits of landscape.

(1) Some researchers have proposed building-integrated vegetation and its design strategies, including maintaining permanent vegetation on buildings to maximize carbon sequestration rates. Consider spatial ecological factors, such as habitat quality and species selection, to specify vegetation design strategies [9].

(2) For green lands, researchers have also proposed to conduct multi-shape and mathematical induction on green plant communities, summarizing the high carbon sink benefits of green plant communities. Based on the results, provide guidance for improving the carbon sink benefits. Through the i-Tree Eco model, the carbon storage and carbon sequestration capacity of different tree species are evaluated. The model estimates the CO_2 capture capacity of trees and shrubs by using biomass and allometric growth equations, combined with plant parameters such as diameter at breast height (DBH), crown height, crown width, and crown light exposure, as well as climatic conditions, providing data support for urban greening planning [10].

(3) Vertical farming is also a thriving bioenergy and carbon capture technology, which has the functions of reducing greenhouse gas emissions and increasing soil carbon content. Currently, small-scale, high-value, short-cycle green leafy vegetables have been planted in some areas [11].

3. Feasibility Study and Popularization Barriers of Carbon Capture and Storage Technology in the Field of Construction

One of the reasons affecting the promotion of CO_2 capture and storage technology in construction materials is that the cost of new technology may be higher than that of old technology, which will affect the enthusiasm of enterprises for the application of new technology. New technologies face high risks, high costs, and difficulties in financing [12].

In addition, there are different conclusions about the impact of CO_2 mineralization technology on the physical properties of building materials. Some recognize the feasibility of CO_2 mineralization technology, while others believe that the performance of these new materials produced has no advantages or even disadvantages compared to traditional materials, which may be related to the specific process and final degree of carbonization. The pre-carbonization during the concrete mixing process and the accelerated carbonization during the curing process make the structure dense and have a positive effect on the strength. The permeability of concrete is also reduced, and its resistance to high temperatures, weathering, freezing and thawing, and corrosion by chloride and sulfate ions is improved. However, excessive carbonation can cause the pH of the concrete to decrease, and once it reaches a certain level, subsequent hydration may also be difficult to restore the pH to its normal value of 13, which increases the risk of corrosion of the steel reinforcement and becomes a key factor limiting curing techniques. This will make this part of the technology more suitable for prefabricating non-reinforced concrete products and block products [13].

There are also many obstacles in the practical application of vertical farming technology that affect its popularization. Firstly, the startup costs for establishing a controlled environment and implementing infrastructure are high, as are the operational costs caused by skilled labor, rent, and energy costs to maintain the controlled environment. In addition, the large size and slow life cycle of some crops also pose challenges to the applicability of vertical farming.

4. Suggestions for the Development of Carbon Capture and Storage Technology in the Architecture Field

In the future, urban planning should increasingly adopt various emerging assessment and prediction models that have been proven effective. By prioritizing people and achieving a balance between development and protection, the role of carbon sequestration should be recognized as a crucial factor.

Mineralization is a promising carbon sequestration technology for construction. It should be promoted from the perspective of technology, with the aim of reducing costs while ensuring the performance of building materials, and optimizing formulations and process flows. In terms of raw materials, try to use lower-cost and waste materials as materials to form a cost advantage over traditional technologies. The system of carbon trading, namely carbon emission rights, should be attempted to build. Research shows that after the introduction of carbon trading, the economic benefits of emerging technologies related to carbon capture and storage have advantages over traditional technologies, as they can stimulate demand, reduce risks, and accelerate deployment [12]. This advantage can also enhance the industry's enthusiasm for the research and development and use of new technologies, which is more conducive to the development of carbon capture and storage technology. Tax relief and investment subsidies are also feasible attempts to help enterprises survive the initial adoption of technology. Increase the use of recycled aggregates and other construction waste to achieve the recycling and reuse of construction waste, while absorbing CO_2. Developed countries generally have a high utilization rate of construction waste, and other developing countries should set this level as a goal, which will provide greater room for the conservation and utilization of building materials and the reduction of CO_2 emissions during the production process of building materials, which can better protect the ecological environment. Since carbon emissions or capture is a process throughout the life cycle of buildings, and the performance of building structures is also a long-term indicator, differences in the carbonization process and degree can even affect the physical properties of building structures. Life cycle assessment techniques should be introduced to evaluate mineral carbonation and optimization.

In terms of landscaping, trees should be chosen for their higher potential for carbon storage compared to shrubs, but shrubs should also serve as a barrier below the planting layer. To enhance the carbon sink benefits of green spaces, measures such as selecting high carbon sink tree species, tree diameter at breast height within high carbon sink ranges, a higher diameter structure (plant height and crown width), and a higher planting density within the cost-benefit cost ceiling can be taken [10].

5. Conclusion

Carbon capture and storage technology has many applications in the field of architecture, including urban planning, building materials, landscape, and related fields. In terms of urban planning, there are mainly some emerging assessment models and decision-making aids to achieve better planning for carbon sink benefits. The effectiveness of such tools has been widely demonstrated, and more promotion of relevant technologies and experiences should be carried out. The construction industry is an important source of global carbon dioxide emissions, and the production of building materials is a key factor. For the reuse of building materials waste, some traditional projects that emit carbon dioxide will be transformed into ones that use carbon dioxide as one of the raw materials for capture and storage, making it an economic sector that can make a key contribution to global carbon reduction. Many technologies and methods in building materials have already been put into commercial operation, which has added impetus to the development of carbon capture and storage technology. Continuous investment should be made in this area to improve the deficiencies of various technologies. Carbon reduction technology in the field of landscape design requires both in-depth research on traditional ways and the adoption of new technological approaches to make the entire field more refined.

This study summarizes existing carbon capture and storage technologies by reviewing relevant literature and lists multiple technical routes. However, there is a lack of analysis of the current role and weight of each route. Due to the lack of systematic evaluation methods, suggestions for future development remain at the level of solving problems in the popularization of various technologies. Moreover, due to insufficient exploration of some cutting-edge technologies, the technologies listed are mostly mature and have been developed for a long time. However, this article aims to summarize the field of carbon capture and storage in architecture, which has been less systematically addressed, and to provide suggestions for technological development. Therefore, it is of significance for the development of low-carbon and green buildings.

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