

CO₂ Sequestration in “Blue Carbon” Systems: Research Progress on the Synergy between Ocean CO₂ Storage and Coastal Blue Carbon

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Abstract. The carbon dioxide content in our atmosphere is increasing rapidly. This means that we need better methods to capture and store carbon, and these solutions can work effectively for many years and can be scaled up to a larger scale. Among the various technologies that can be used to reduce carbon emissions, traditional carbon capture and storage methods show promising potential. These methods can reduce carbon emissions by billions of tons every year. However, we need to understand their limitations. These systems require large amounts of energy to operate, and the safety of long term carbon storage remains questionable. In contrast, nature itself offers a powerful solution through the blue carbon ecosystem. Coastal environments such as mangroves, salt marshes, and seagrass meadows have demonstrated extraordinary capabilities in capturing and storing carbon. This work explores how carbon capture systems and natural blue carbon environments can work effectively together. Marine carbon sequestration solutions represented by seabed carbon dioxide storage and Marine alkalization enhancement technologies can achieve the goal of rapid and large-scale carbon removal. Meanwhile, the unique anoxic sedimentary environment and vigorous biological activities in the blue carbon ecological zone jointly enhance the stability of carbon storage, effectively reduces the possibility of leakage, and improves the ecosystem's resilience to environmental pressure. The experimental research results further confirm that in an environment with moderate increased carbon dioxide concentration, the primary productivity of ecosystems such as seagrass beds and mangroves has been significantly enhanced. This discovery provides a new idea for improving the carbon sequestration effect.

Keywords: Ocean carbon storage; CO₂ storage; blue carbon; ecosystem services; climate change mitigation.

1. Introduction

One of the core driving force of contemporary climate change is the rapid increase in carbon dioxide content in the atmosphere. Since the industrial age, the global concentration of carbon dioxide has been continuously increasing from around 280ppm, and by 2022, it had even surpassed the 420ppm mark. This figure has already surpassed the key security line set by the Paris Agreement - the goal of keeping the global temperature rise within 1.5 degrees Celsius above pre-industrial levels. The continuous combustion of fossil fuels remains the main source of carbon dioxide emissions. Specifically, the power generation and heating sector contributed approximately 47% of the emissions, the transportation sector accounted for 25%, and industrial activities such as steel manufacturing, cement production, and petrochemicals generated 18% of the emissions. It is important to understand that even if we do our utmost to reduce emissions, some industries will continue to generate carbon pollution in the coming decades. This is because the particularity of its manufacturing process. If we want to achieve the goal of carbon neutrality, it is absolutely necessary to develop technologies that can capture carbon dioxide on a large scale and store it safely for a long time (Hilmi et al., 2021). The first method employs machines and technology, while the second relies on natural systems such as forests and oceans. Both of these methods are valuable, but they also have their own weaknesses. At present, several problems are hindering the development of this technology. These factors include the large amount of electricity required to capture and compress carbon dioxide, expensive equipment and operating costs, unsolve mysteries about whether carbon can be safely stored, and concerns from some communities about potential environmental damage, which made them worried about supporting these projects. The current technical routes mainly cover various methods such as pre-

combustion capture, post-combustion capture, and direct capture from the air. These technologies rely on different separation methods, including chemical absorption processes, physical adsorption processes, membrane separation, technology and low-temperature condensation, etc. Although the feasibility of these technologies has been confirmed in laboratory research and demonstration projects, obstacles in terms of scalability and economy still need to be overcome to achieve large-scale commercial application (Hori, Bayne, & Kuwae, 2019).

Against this backdrop, "blue carbon" has gained significant attention in recent years as a nature-based climate response approach. The blue carbon ecosystem composed of mangroves, coastal salt marshes, and seagrass bed has been proven to be one of the most efficient carbon sequestration ecosystem types in the world. These systems achieve a carbon storage efficiency four times that of terrestrial forests by burying organic carbon in oxygen-deficient sedimentary layers. Previous studies have clearly pointed out that these ecosystems also provide a number of important ecological services: they can effectively resist the invasion of storm surges, purify water quality through natural processes, and provide a living environment for rich Marine life (Hori, Bayne, & Kuwae, 2019). Global assessment studies have further confirmed that strengthening the protection and restoration of these ecological areas can not only effectively absorb carbon emissions generated by human activities, but also significantly enhance the ecological resilience of coastal areas (Hilmi et al., 2021). However, these precious ecosystems are facing increasingly severe threats. The unreasonable development of coastal areas, increasingly serious pollution problems, the continuous expansion of aquaculture, and the persistently rising sea level have jointly led to the continuous deterioration of the survival conditions in these ecological regions (Howard et al., 2017). Research data show that nearly one-third of mangroves and seagrass beds have disappeared worldwide, which directly weakens their significant contribution to achieving the carbon neutrality goal.

2. CO₂ storage pathways and technological progress

2.1 Pre-Combustion Capture

The core application scenarios of pre-combustion carbon capture technology are mainly concentrated in the integrated gasification combined cycle power generation system. In this process, carbon-containing fuels such as coal or biomass first need to undergo special treatment. Under the conditions of high pressure and high temperature coexisting, the gasification reaction is completed. Ultimately, a synthetic gas mainly composed of carbon monoxide and hydrogen is formed. Subsequently, these carbon monoxide components will fully interact with steam through the water-gas shift reaction, converting into carbon dioxide and additional hydrogen. Firstly, the level of carbon dioxide remains between 15% and 50%, which is highly concentrated. Secondly, the entire system operates continuously under high pressure conditions. Once carbon dioxide has been separated and cleaned, it can be pressurized. Then, this compressed carbon dioxide can be stored underground or actually used in various applications. Meanwhile, the hydrogen produced in this process can be used as an alternative to clean fuels. It may be applied in the production of power or electricity. It is very effective in capturing carbon emissions of 85% to 95%. Moreover, the pressure of the airflow is natural to cut short the energy needed in compressing it. Nonetheless, this is not a general case and there are a number of issues that are reducing the large-scale adoption of this technology. The existing energy system needs a considerable modernization, and the special equipment, needed to implement gasification, is highly expensive to build. Numerous sophisticated technologies are also incorporated in the entire installation and they have to go hand in hand. These aspects justify why pre-combustion carbon capture is not a very popular practice used in commercial activities yet (Hilmi et al., 2021).

The new frontier is to use carbon capture techniques with technologies that will convert the captured carbon into products that are useful instead of just storing the carbon. A research team in China has developed an artificial ocean carbon system that has a high potential in this area. Their system operates in a different manner compared to the conventional pre-combustion capture systems, but they have the same basic concept that is, they both capture carbon and transform it in a more

useful form. Other innovative approaches of some teams involve the incision of carbon dioxide in seawater by utilizing electric current. They use a special catalyst which has bismuth to convert the carbon dioxide that they have captured to formic acid. Moreover, microorganisms have been genetically engineered and scientists can utilize this formic acid in making other more valuable products. An example is succinic acid which can be used to create plastics which can be broken in the environment. This type of capture and conversion system has been operating over 500 hours without a hitch. Its capture rate of carbon is above 70%, and the initial estimation indicates that the price of processing one ton of carbon dioxide through the mechanism is around \$230. This shows a significant new method of climate technology. The answer to this question is that as we merge the various disciplines like electrochemistry and bioengineering we will be able to utilize the captured carbon to create products which people are willing to buy. This will render carbon management more cost effective and develop new opportunities to deal with climate change.

2.2 Post-Combustion Capture

Many researchers believe that post-combustion carbon capture is the most developed and commonly used carbon capture method today. It has importance in power plants and industries that have high consumption of energy like producing cement and steel. The principle of this technology is extremely simple: to weed out the carbon dioxide in the smoke created as we burn coal or natural gas. The best thing about the approach is that it is highly adaptable. Being not dependent on the reconstruction of the current industrial plants, the company can add it to the current factory without making costly adjustments. This renders it a feasible option in abating pollution in the current plants. A majority of systems adopt a process termed as chemical absorption and this is dependent on an amino solution. To begin with, burning fuel releases smoke which is cooled. It is then added to a special chamber, where it is combined with an amine solution. When the carbon dioxide of the smoke enters into contact with this solution, there takes place a chemical reaction that fixes the carbon dioxide in the liquid. This liquid that is rich in carbon is then pumped to a different unit. Chemical bonds are able to be broken under heat releasing pure carbon dioxide that can be collected. In the meantime, the initial solution is recuperated and it is returned to capture additional carbon dioxide making it a cyclic process.

Although this method captures approximately 90% of the carbon dioxide, it requires a large amount of energy to operate. The greatest cost comes from the regeneration of the solvent, that is, the process of removing captured CO₂. For each ton of carbon dioxide treated, this solution typically uses 2.5 to 4.0 gigajoules of energy (Howard et al., 2017). In addition, the equipment is at risk of corrosion, and the by-products generated during solvent degradation also pose environmental problems. Some scholars have linked this technology to Marine conservation. Testing how to utilize captured carbon to help our oceans instead of storing it underground. Pure carbon dioxide can combine with minerals or industrial waste to form an alkaline solution. Incorporating these solutions into the sea water will make the ocean take in more carbon dioxide out of the atmosphere. Carbon is stored as a bicarbonate that is a natural element of the seawater as well as alleviates the ocean acidification. This is especially significant to vulnerable Marine habitats like the mangroves, seagrass beds as they form vital natural carbon sinks. On the bottom of the sea stable minerals grow. Even though these comprehensive methods are still on early testing phases, they are a significant advancement of carbon capture technology as it is no longer considered a mere pollution treatment but rather a component of a complex system that handles carbon and safeguards valuable Marine ecology.

2.3 Chemical absorption

This process is carried out by a reversible reaction of the amine solution and carbon dioxide molecules. Although the carbon dioxide in the factory smoke may be diluted down to 10-15%, it is still effective. The carbon dioxide molecules are first captured in the amine solution at 40 to 60 degrees Celsius at first in a special container. Subsequently, the carbon dioxide enriched solution is

pumped to a different unit where the solution is heated to 100-140 degrees Celsius. In this heating, pure carbon dioxide gas is set free and pressed and stored. In the meantime, the cooled solution goes back to the loop. It is also able to remove 85-95% of carbon dioxide even in the presence of other gases like nitrogen and oxygen. This technology is particularly suitable for large amounts of industrial waste gas containing a small amount of carbon dioxide. This makes it feasible to update existing factories rather than build brand-new facilities. However, some real challenges have hindered the wide application of this technology. The most serious problem is how much energy is needed to regenerate the solvent. Treating each ton of carbon dioxide consumes 3 to 4 gigajoules of electricity, reducing the overall efficiency of power plants by 8 to 12%. In addition, when exposed to oxygen, heat and other chemicals in the smoke, the solvent will gradually decompose. It implies that the factories need to constantly inject new solvents, and at times hazardous by-products are produced. There is the problem of rusting of equipment, and loss of solvents to the atmosphere and harm to the environment because of the degradation of chemicals all of which are added to the long-term expenses.

Other researchers are working on better amine substances like piperazine which is more appealing to carbon dioxide molecules. The carbon dioxide can also be moved faster by these new formulas and it retains its chemical structure. The other category is referred to as steric hindered amines and AMP belongs to this category. Simultaneously, there are also some potential positive alternatives which are investigated. These are special solvents which switch between liquids, ionic liquids and amino acid salts. The exciting part of these materials is that, they do not use as much energy to charge and also they are more environment friendly. Recent studies have been dedicated to the amalgamation of chemical absorption and membrane filtration. This approach has allowed scientists to develop a system where each technology complements the other by means of combining these two approaches. The more interesting fact is that this technology is currently expanding beyond factories and industrial plants. It has also been used in the management of carbon in the Marine environment and this shows how innovation can go beyond the normal boundaries. The high-purity carbon dioxide obtained through this process can be used in the ocean alkalinity enhancement program: by generating alkaline substances through controlled reactions with silicate minerals and injecting them into the ocean, it can not only increase its carbon sink capacity but also alleviate the acidification trend. The deep integration of this engineering system with the natural cycle provides new technical support for maintaining the health of coastal blue carbon ecosystems by alleviating the pressure of ocean acidification on the ecosystem..

3. CO₂ Ocean storage mechanism

Marine carbon sequestration is another engineering approach that can be integrated with the blue carbon system. Unlike terrestrial geological storage, Marine carbon sequestration relies on the high solubility of seawater and the natural capacity of Marine systems for temporary storage. The methods include directly injecting water columns to inject carbon dioxide into the middle or deep layers of the ocean, allowing it to dissolve in the seawater. Although this method is technically feasible, there are problems of local acidification and environmental risks to Marine life. And seabed geological storage, that is, injecting carbon dioxide into saltwater aquifers or depleted oil reservoirs beneath the seabed, provides a higher degree of stability. When such storage facilities are located near nearshore blue carbon ecosystems, they can benefit by leveraging natural sediment interactions that limit leakage. Ocean alkalinity enhancement (OAE) reduces the risk of acidification by adding alkaline minerals to enhance the ocean's ability to absorb and store carbon dioxide in the form of bicarbonate. This method can indirectly improve the growth conditions of seagrass and mangroves by stabilizing the chemical properties of water bodies (Hilmi et al., 2021). Despite the promising prospects of Marine storage, technical and administrative obstacles still exist. Monitoring leaks, ensuring continuity and addressing cross-border legal frameworks remain urgent problems to be solved.

4. Coupling mechanism of ocean blue carbon and storage

Marine carbon sequestration is another engineering approach that can be integrated with the blue carbon system. Unlike terrestrial geological storage, Marine carbon sequestration relies on the high solubility of seawater and the natural capacity of Marine systems for temporary storage. The methods include directly injecting water columns to inject carbon dioxide into the middle or deep layers of the ocean, allowing it to dissolve in the seawater. Although this method is technically feasible, there are problems of local acidification and environmental risks to Marine life. And seabed geological storage, that is, injecting carbon dioxide into saltwater aquifers or depleted oil reservoirs beneath the seabed, provides a higher degree of stability. When such storage facilities are located near nearshore blue carbon ecosystems, they can benefit by leveraging natural sediment interactions that limit leakage. Ocean alkalinity enhancement (OAE) reduces the risk of acidification by adding alkaline minerals to enhance the ocean's ability to absorb and store carbon dioxide in the form of bicarbonate. This approach is also an indirect way of enhancing the growth environment of seagrass and mangroves because it stabilizes water body chemistry (Hilmi et al., 2021). Even after the Marine storage has good prospects, there are still technical and administrative barriers. The tracking of leaks, continuity and cross-border law is also an urgent issue to be resolved.

5. Future and prospect

5.1 Challenges

Despite the growing awareness in combining Marine carbon storage and coastal blue carbon ecosystems, most challenges are yet to be encountered on a large scale. Our primary issue is the fact that we are not fully aware of the reaction of these complex natural systems to prolonged exposure to carbon dioxide. A number of significant natural processes can be influenced. These are modifications in the structure of microorganisms, modifications in the chemical characteristics of sediments at seabed, and the changes in the functions of the whole ecosystem. Even slight alterations in such spheres can be followed by unpredictable outcomes. This is particularly among systems that are utilized in monitoring, reporting and certifying stored carbon. One of the primary technical challenges that should be overcome is developing effective MRV programs that can be used in the ever-evolving Marine environment. Moreover, the human activity can modify the composition of the sediments or disturb the existing Marine biomes. This has given rational fears to individuals regarding the preservation of health and operation of the ecosystems. Lastly, policies and management ways also have their apparent weaknesses. No definite regulations exist on the ownership of the stored carbon. The collaboration between various states should be enhanced, and the carbon market has been retarded in accommodating such combined approaches. All these have impeded international collaboration and funding of such projects.

5.2 Future Directions

There are three areas that we need to put our combined efforts together, which are scientific research, technological development, and improvement of policies. The other phase of the work ought to be to carry out field tests in different coastal conditions. Middle-sized demonstration projects should be given special consideration and they assist in relating laboratory findings to real-life applications. With the development of the computer models capable of recreating the chemical cycles and growing of the ecosystem in the nature we are able to predict the long-term results of the storage of carbon and the development of the environment better. It is on this background that the creation of so-called Blue Carbon Storage Coupling Index (BCSCI) will come in handy. The measurement system will evaluate the project by considering a variety of factors, such as the rate of carbon storage, the degree to which the habitat quality will improve, and the degree to which the local communities will be helpful. Utilize satellite and ground sensors at the same time. The holistic solution will monitor carbon flows and other significant environmental measures in real time, which will give credible

information to the managers on decision making. Moreover, such all-encompassing strategies are to be included in the international climate agreements and system of carbon market. The verification of the results by independent experts will facilitate attracting investment and make the project credible ensuring that its progress is announced. This involves the dismantling of the boundaries between the various research areas. We require a working network that incorporates the association of Marine engineers, environmental scientists, social researchers and policymakers. This hybrid solution combining engineering and natural carbon storage techniques can be of great benefit in advancing climate objectives and assisting in building the coastal environments more resistant to climate change and capable of sustaining various life forms.

6. Conclusion

This work demonstrates that combining anthropogenic carbon storage methods with natural blue carbon environments opens up a promising path for addressing climate change. Engineering carbon capture systems can store large amounts of carbon in a shorter time. However, there are two major issues that limit their wide application: the expensive nature of these projects and the uncertainty over whether the stored carbon can remain safe in the long term. On the other hand, coastal blue carbon systems such as mangroves and seagrass meadows operate differently. Their carbon capture occurs gradually through natural processes. Despite this, they offer special advantages that technology alone cannot provide. These ecosystems capture carbon through Marine sediment processes and also bring multiple environmental benefits. These measures include protecting various species, cleaning our waters and safeguarding coastlines from erosion. When these techniques are combined with natural methods, they will enhance each other's effectiveness. Artificial systems increase the amount of carbon entering the Marine environment, while coastal habitats take advantage of their unique soil conditions to make carbon storage safer and more sustainable. We have introduced the "Blue Carbon Storage Coupling Index". This tool will provide a standard method for evaluating the performance of these comprehensive projects. We need better cooperation among different research fields and stronger international partnerships. Combining carbon storage technology with blue carbon conservation not only represents scientific progress but is also a necessary step to create a sustainable future for society and nature. By ingeniously integrating technological solutions, environmental restoration and community engagement, this comprehensive approach can provide adaptable and scalable methods for managing global climate challenges.

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