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Applications of Biotechnologies in Carbon Capture and Sequestration

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Abstract. Global greenhouse gas concentrations have been steadily increasing without sign of slowing down since industrialization. The most significant greenhouse gas, CO_2, has reached an unprecedented peak. CO_2-negative emission technologies are a good way to reduce atmospheric CO_2 concentrations. Among these, bioenergy carbon capture and sequestration (BECCS) is considered as a key technology for stabilizing global warming at a low level in the future. This paper reviews biotechnology applications in carbon utilization and carbon sequestration, analyzing their principles, advantages and disadvantages, as well as the current status of the application. Regarding carbon utilization, focus is placed on bioethanol production, biomass combustion power generation and collaborative high-value chemical production from CO_2 and biomass. Bioethanol production can effectively reduce costs, enhance energy efficiency in biomass energy utilization, minimize reliance on fossil fuels, and optimize overall carbon utilization. Biomass combustion power generation can mitigate pollutant emissions and decrease carbon emissions from power plants. Collaborative high-value chemical production from CO_2 and biomass enables the production of valuable chemicals while reducing the dependence of chemical plants on oil and natural gas as raw materials, thereby expanding CO_2 utilization pathway. Regarding carbon sequestration, this paper introduces blue carbon sequestration with its significant long-lasting effects on carbon storage capacity. Additionally, terrestrial carbon sequestration is discussed to highlight its dual benefits of capturing carbon while improving soil properties and promoting crop growth.

Keywords: Carbon Utilization, Carbon Sequestration, Biotechnology, BECCS.

1. Introduction

1.1. Environmental and Climate Issues

Global land-ocean temperatures have increased by at least 1.1℃ since the preindustrial period 1880 [1]. However, certain studies suggest that the Earth is still experiencing an ice age, indicating that a decline in temperature is the natural trend for normal Earth conditions [2]. Current global warming is not normal. Global warming encompasses more than just numerical increases; its impact should not be underestimated. The ecological environment is the most direct impact. For instance, rising temperatures promote water evaporation, accelerate glacier melting, and intensify the water cycle, resulting in wetter humid areas and drier arid regions. This leads to heightened occurrences of severe weather phenomena,

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including but not limited to floods, droughts and wildfires [1]. Furthermore, the local species will face severe devastation due to significant alterations in the ecological environment. According to statistics, since industrialization began, there has been an approximately 1,000-fold increase in the rate of global species extinction [3].

Global warming not only affects ecology but also profoundly impacts human society. The rise in extreme weather events like droughts and floods imposes economic burdens on a global scale. Statistics indicate that if global temperature increases by 2℃, there would be an approximate loss of 2% in global GDP; if temperature rises by 3℃, this figure could reach between 10% and 12% [4].

The primary driver of global warming can be attributed to human activities since the advent of industrialization. Since industrialization started, humankind has heavily depended on fossil fuels like oil, natural gas and coal, accounting for above 80% of worldwide energy consumption [1]. The widespread use of fossil fuels has caused substantial carbon dioxide emissions that disrupt the Earth's carbon cycle and rapidly increase atmospheric CO_2 concentration. Specifically, atmospheric levels of CO_2 have increased from around 280 ppm before industrial times to almost 410 ppm in 2018 [1].

1.2. CCUS Technology Introduction

To mitigate the impact of global warming, the objective of the Paris Agreement is to regulate the rise of mean temperatures to less than 2℃ compared to pre-industrial levels, while making endeavors to restrict it below 1.5℃.

According to the IPCC, Intergovernmental Panel on Climate Change, report, achieving 2℃ warming target necessitates attaining net zero carbon dioxide emissions by 2070. To achieve the more ambitious goal of limiting warming to 1.5℃, humanity must reduce CO_2 emissions by 45% from 2010 levels by 2030 and ultimately reach zero emissions around 2050 [1].

Technologies for the removal of carbon dioxide such as carbon capture, utilization and storage (CCUS) are indispensable for early attainment of net zero emissions [1]. CCUS refers to capturing CO_2 from industrial production, energy utilization or directly from the atmosphere and either utilizing or storing it at specific locations in order to diminish atmospheric CO_2.

1.3. Advantages and Application of Biotechnology

Among CCUS technologies, physical, chemical, and biological approaches are the primary methods. For instance, direct air carbon capture and storage (DACCS) and bio-energy with carbon capture and storage (BECCS) are used.

DACCS catches CO_2 from ambient air using physical/chemical techniques before releasing treated gas back into the atmosphere. However, due to the low concentration of CO_2 in the air, this technology requires a large intake volume, resulting in high energy consumption. In contrast, BECCS is considered a more viable negative emission technology as it harnesses biomass energy stored by solar energy in organic matter as renewable chemical energy with minimal pollution levels and widely applicable for heating, power generation or transforming fuel/chemical raw materials.

The focus on traditional CCUS technology often overshadows the lesser-understood application of biotechnology in carbon utilization and carbon sequestration. Therefore, this paper discusses the biotechnology's fundamental principles, advantages/disadvantages, and application status.

2. Biotechnology-Based Carbon Utilization

In terms of carbon utilization, biotechnology covers extensive applications, including biomass power generation, biofuel production, biogas utilisation, and bio-based materials and chemicals. This paper primarily examines three key areas: ethanol production as a biofuel, power generation through biomass combustion, and the collaborative production of high-value chemicals using CO_2 and biomass.

2.1. Bioethanol

Currently, bioethanol is extensively used as a renewable biofuel and is also regarded as one of the potential alternatives to petroleum. In comparison with petroleum fuel, bioethanol offers numerous

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advantages: (1) renewable, it can be repeatedly obtained through biomass cultivation; (2) green, lower greenhouse gas emissions; (3) environmental protection, it emits fewer harmful gases after combustion, thereby mitigating air pollution; (4) biodegradable, it causes less harm to the environment if leaked. However, bioethanol cannot fully replace oil due to its high production cost and low energy density compared to oil's properties.

Bioethanol can be produced from three different feedstocks [5]. First-generation feedstocks include sugar-based options (cane, beet, sorghum and fruit) and starch-based options (corn, wheat, potatoes and cassava). The second generation utilizes lignocellulosic crops or waste feedstocks like corncob, straw and wood waste. Lastly, the third generation involves algal biomass as a feedstock.

The choice of materials is heavily influenced by geography. For instance, there is a significant corn production in the western part of the United States, corn is used as a feedstock for bioethanol production. Similarly, Brazil, the largest producer of sugar cane globally, uses cane as their primary feedstock to produce bioethanol.

Although the raw materials utilized differ, the production process essentially consists of three main steps: (1) pretreatment and crushing of the raw materials; (2) hydrolysis to convert them into fermentable sugars; (3) anaerobic fermentation of these sugars into ethanol. Taking lignocellulose as an example, this involves pretreating selected lignocellulosic materials like wood, straw or waste paper for efficient subsequent processes; enzymatic hydrolysis by adding them to a tank with appropriate enzymes at specific temperatures to transform them into fermentable sugar; and finally transferring these enzymatically-hydrolyzed substances along with fermentation strains into a fermenter for conversion into ethanol and carbon dioxide. In contrast to first-generation bioethanol, which mainly relies on food crops as feedstock, although simple technology can be employed for bioethanol production, it competes with land use rights for food crops and drives up prices.

Switching to lignocellulosic materials for bioethanol production offers lower cost, less land occupation, and abundant raw materials at low prices compared to corn, wheat, sugarcane, and other crops. However, the pretreatment cost of this method is high.

As a third-generation raw material, microalgae shows high photosynthetic efficiency and has the potential to accumulate significantly more biomass energy per unit time than traditional energy crops. This theoretically provides a substantial advantage in ethanol production. Nevertheless, the current stage of technology is still focused on research and development. The technology has not yet reached the level of industrial production.

2.2. Biomass Combustion Power Generation

Combustion is the simplest and most efficient way to use biomass. Biomass combustion for power generation can be categorized into two types: pure biomass combustion as well as co-firing with coal.

Pure biomass combustion refers to using biomass as a solid fuel, either through direct combustion or combustion after compression, to harness its released heat for power generation. The primary sources of raw materials from pure biomass include agricultural, urban, and industrial waste. Pure biomass fuels exhibit excellent combustibility and emit reduced levels of pollutants such as nitrogen oxides and sulfur dioxide. Furthermore, they result in zero net carbon dioxide emissions. However, simple direct combustion of biomass often fails to achieve complete oxidation, easy to produce nitrogen oxides and particulate matter which cause environmental pollution. Also, biomass fuels such as potassium (K) and chlorine (Cl) have high inorganic content, leading to excessive ash production during direct combustion. This ash can easily obstruct pipelines or accumulate in boilers. Moreover, the heat transfer coefficient of these ash deposits is only 1/40 of that of steel, resulting in uneven heating within boilers and potentially leading to pipeline ruptures or boiler explosions. Furthermore, elevated chlorine content in the ash can cause corrosion issues that impact normal power plant operation [6]. As early as 1998, Denmark BWE constructed a straw-based bio-burning power plant and subsequently designed and built wood chip and waste burning power plants in subsequent years. In 2006, Elyan had the largest straw-based power plant with an installed capacity of 38.0MW [7].

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Compared to burning pure biomass, the co-burning of biomass and coal can effectively solve issues related to ash and boiler slagging and enhance power generation efficiency in power plants [7]. Moreover, the high volatile content present in biomass not only improves coal burning performance but also reduces pollutant emissions [8]. In terms of carbon emissions accounting, biomass burning is considered as having net zero emissions, so the oxygen-rich co-burning of biomass and coal can significantly decrease carbon emissions from coal-fired power plants. This technology establishes an effective low-carbon fossil energy approach and promotes the development and utilization of clean energy sources such as biomass energy. Therefore, this technology has attracted considerable attention and possesses promising application prospects [8]. However, technology presents certain challenges. The utilization of biomass in this method necessitates more intricate pretreatment due to the disparities in physical and chemical properties between biomass and coal. Furthermore, the co-combustion of biomass and coal can be influenced by environmental elements, including airflow and temperature, which impact combustion efficiency. Consequently, real-time control of the biomass-to-coal ratio becomes imperative for ensuring stable power generation through combustion.

Biomass and coal co-firing technology with oxygen-enriched combustion has been widely implemented. In 2008, the Drax power plant in the United Kingdom converted from its original thermal power generation system to a biomass-coal hybrid pulverized fuel power plant, resulting in an annual reduction of around 2 million tons of CO_2 emissions [7]. Japan also aims to construct biomass co-firing power plants with a total installed capacity of approximately 5GW by 2030.

2.3. CO_2 Collaborates With Biomass To Produce High-Value Chemicals

Co-production technology utilizes CO_2 and biomass to produce high-value chemicals. Biomass is abundant in carbon, oxygen, and complex functional groups, allowing the formation of various products through oxidation reactions. When biomass is combined with low-cost, non-toxic and easily recyclable CO_2, which oxidation type or weak acidity in water can catalyze to enhance enzyme activity and product conversion rates [9].

This innovative technology utilizes two readily available carbon resources, biomass and CO_2, to convert low-value carbon resources into high-value ones. It offers significant economic benefits and reduces the reliance of the traditional chemical industry on fossil fuels like petroleum while achieving negative carbon emissions. Moreover, this technology can be synergistically combined with other carbon utilization technologies, such as biomass combustion power generation, where the captured high-concentration CO_2 from fuel combustion in power plants is catalytically transformed into valuable carbon resources, thereby enhancing cost-effectiveness and efficiency. However, it should be noted that this technology faces challenges related to its relatively low catalytic efficiency and stability levels. Additionally, addressing the complexities associated with solid-liquid-gas three-phase adsorption and transformation involving CO_2 presents further research difficulties [9].

In the field of collaborative CO_2 and biomass production, numerous scholars have made noteworthy contributions. They achieved the complete process of biomass conversion into high-value products. For example, Morais et al.[10] achieved the conversion of wheat straw into xylose through high-pressure carbon dioxide treatment, followed by a CO_2-catalyzed dehydration reaction to produce valuable furfural and its derivatives. Similarly, Nanao et al.[11] successfully hydrogenated furfural and furfuryl alcohol to tetrahydrofurfuryl alcohol (THFA) using an activated carbon-supported Pd catalyst under high $H2/CO_2$ pressure, effectively enhancing the value of low-value carbon resources.

3. Biotechnology-Based Carbon Sequestration

Carbon sequestration technology can be categorized into two distinct groups: abiotic carbon sequestration technology and biotechnology-based carbon sequestration technology. Abiotic carbon sequestration encompasses geological, mineral, marine, and other methods achieved through physical and chemical reactions. Biotechnological carbon sequestration refers to capturing and storing atmospheric carbon dioxide through biological photosynthesis, which also plays an essential part in the

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carbon cycle in a global scale. Biological sequestration is considered more reliable and cost-effective compared to abiotic methods.

Based on environmental variations among organisms, biological carbon sequestration can be classified as blue carbon sequestration and terrestrial carbon sequestration [12].

3.1. Blue Carbon Sequestration

The ocean has a significant impact on the carbon cycle since organisms in the marine can account for over half of all living organisms' sequestered carbon. Blue carbon refers specifically to that which is captured by marine life. Its sinks exhibit considerably longer storage periods when compared with terrestrial ones. While terrestrial ecosystems like forests and grasslands typically store their captured CO_2 for several decades at most, blue carbon sinks can persist for hundreds or even thousands of years [12]. Consequently, blue carbon sequestration showcases attributes characterized by high-capacity retention capabilities alongside enduring effects on reducing atmospheric greenhouse gases. However, the natural environment will significantly impact the carbon sequestration capacity of marine ecosystems. In other words, the factors influencing marine ecosystems – including extreme storms, climate change, and rising temperatures – are more challenging to control compared to terrestrial ecosystems. This introduces uncertainty into the carbon sink function of blue carbon [13].

The effective safeguard and strategies for preserving the marine ecosystem and the utilization of marine resource advantages are currently crucial strategies for optimizing marine carbon sequestration.

The coastal ecosystems, including mangroves, seagrass beds, and tidal marsh, are globally acknowledged as operational blue carbon ecosystems with significant potential for carbon sequestration per unit area. However, these fragile coastal ecological environments are susceptible to pollution-induced degradation that spreads rapidly, leading to the loss of blue carbon ecosystem functions and even the release of CO_2 stored in marine sediment.

Additionally, due to global warming and other factors, certain components of the marine ecosystem have transitioned from being carbon dioxide sinks to becoming carbon dioxide sources, such as coral reefs. This shift can be attributed to increased dissolution of CO_2 into the water, leading to carbonic acid formation and intensifying ocean acidification. Consequently, this process reacts with CaCO3 to release additional CO_2. Furthermore, some scholars posit that calcifying organisms also emit carbon dioxide during their calcification processes [12].

3.2. Terrestrial Carbon Sequestration - Biochar Technology

The process of thermochemical conversion of biomass under hypoxia conditions results in the formation of biochar, a carbon-rich solid substance. One important application of terrestrial biochar is its incorporation into soil, which enhances soil carbon content and facilitates the remediation of contaminated soil.

Its unique aromatic structure does not solely determine the carbon sequestration of biochar, but also influenced by its abiotic and biological interactions with soil components throughout its environmental life cycle. Firstly, biochar is highly carbon-intensive, with an average carbon retention time exceeding 2500 years, enabling efficient carbon storage. Secondly, biochar possesses various pore structures, a large specific surface area, and demonstrates strong adsorption capabilities for soil organic matter,CO_2 and other greenhouse gases. Thirdly, minerals and microorganisms actively participate in the mineralization or complexation processes of unstable (soluble and easily decomposed) or even recalcitrant components within biochar. This enhances soil properties while providing an optimal habitat for soil microorganisms to thrive, promoting the growth of cultivated plants. Consequently, it establishes a robust carbon cycle from biomass to biochar, and back to biomass again-exemplifying a carbon environmental cycle. The application of biochar, however, meets numerous challenges. For instance, it may potentially exert adverse effects on soil health, while the substantial cost associated with its utilization remains a significant impediment [14].

Biochar technology is being applied in Nanjing, China, where it is used in 500 acres of organic rice fields to reduce emissions and increase carbon sequestration. This implementation has resulted in a significant 10% increase in production, sequestration of approximately 130.67 tons of carbon, and an average reduction of net greenhouse gas emissions by 51%. Furthermore, this innovative approach effectively controls disease prevalence and pest infestations when compared to paddy fields without biochar application, specifically witnessing significant decreases (around 20%) in sheath blight incidences as well as notable declines (approximately up to15%) in borer pest infestations.

4. Conclusions

In terms of carbon utilization, this paper primarily focuses on bioethanol production, biomass combustion for power generation, and collaborative production of high-value chemicals using CO_2 and biomass. Biofuel ethanol derived from biomass fermentation has long been extensively utilized. Advanced biological raw materials can reduce costs, fully exploit biomass energy, and enhance energy utilization efficiency. Biomass combustion for power generation takes advantage of the ready availability and high calorific value characteristics, making it an ideal substitute or co-fuel with coal in power plants. This helps minimize pollutant emissions while improving overall combustion performance as well as decreasing carbon emissions from these facilities. Collaborative production of high-value chemicals through the cooperation between CO_2 and biomass employs two readily available, inexpensive, and abundant carbon resources to convert low-value carbon resources into high-value ones when reducing reliance on fossil fuels—a novel approach to chemical product manufacturing.

Biological carbon sequestration can be categorized into blue and terrestrial carbon sequestration. Blue carbon sequestration utilizes the natural capacity of marine ecosystems to store and sustainably sequester carbon, offering advantages such as high storage potential and long-lasting effects. Terrestrial carbon sequestration, exemplified by biochar incorporation into soil to establish a carbon cycle, enhances soil properties and promotes crop growth.

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