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Applications of Biochar on Carbon Capture, Utilization and Storage (CCUS)

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Abstract. The impact of global warming and greenhouse gases on life and the environment on Earth is very prominent. Human activities emitting carbon dioxide and other greenhouse gases have caused many kinds of environmental damage such as typhoons and tsunamis, sea level rise, forest fires, crop reduction, etc. Many countries have proposed net zero emissions by the middle of this century. And carbon capture, utilization and storage (CCUS) technology is a necessary and powerful approach to achieve the goal. Biochar is a porous form of carbon processed from organic waste such as animal waste, animal bones, plant roots, wood chips and wheat stalks. Its use in the environment can help increase the capacity of CCUS. In this article, the use of biochar in the environment and its benefits are briefly discussed. The use of biochar in carbon reduction is then explained in depth, with a focus on the promotion of the CCUS process.

1 Introduction

Climate change and global warming have been the defining issue of this century. Human activities have contributed to global warming by continuously emitting greenhouse gases (GHGs). The global surface temperature was 1.1 °C higher in 2011-2020 than that in 1850-1900. This has resulted in a wide range of adverse effects and associated losses and damage to nature and humans, which would increase with each global warming increase [1]. According to the report, in 2019, approximately 22% of global GHG emissions came from the sectors of agriculture, forestry, and other land use [1]. Net zero CO_2 emissions are necessary to limit human-caused global warming. Whether warming can be kept to 1.5 °C or 2 °C depends mostly on cumulative carbon emissions until the goal of net zero CO_2 emissions is reached and the amount of GHG emission reductions this decade. By the middle of the century, many nations plan to attain net zero GHG or net zero CO_2 emissions. China, as the largest emitter in the world, has taken up about 28% of the carbon emission of the globe. Therefore, China plays an essential role in achieving global net zero emissions by 2050 [2]. Since China has pledged to achieve net zero emissions before 2060, in addition to emission reduction measures, technologies and infrastructure of CCUS need to be expanded [3].

Biochar is a material produced through modification or engineering. A large range of sources can be the raw materials of biochar, including wood waste, crop leftovers, animal manure, forestry residues, etc. [4]. Biochar is now widely used in soil remediation, sewage treatment, and other contaminant control area. Moreover, the following advantages make it a promising material in CCUS: (1) large emission mitigation potential [5]; (2) moderate cost [5,6]; (3) high durability [5,7]; (4) high reusability [8]; (5) environmentally friendly; (6) low energy consumption [6]. This article examines the application of biochar modified in diverse conditions to CCUS in 3 fields: agriculture, construction, and absorption.

2 Biochar applications in CCUS

According to the International Energy Agency (IEA)'s Tracking Report, the annual capture capacity of CO_2 in CCUS facilities is reaching 45 Mt, which implies that the current capacity is far from that in the net zero scenarios [9]. In terms of the Emissions Gap Report 2021, the early analysis demonstrates the enormous potential of biochar to reduce up to 2.56 Gt CO_2e in total emissions annually, or 5.0% of the total world GHG emissions of 51.5 Gt CO_2e [10]. Due to its high CO_2 adsorption capacity, biochar is likely to be used as a sorbent for CCUS. The qualities for using biochar for a variety of environmental applications vary with the properties of the biochar, which are influenced by the feedstock type and production conditions.

2.1 Carbon sequestration and utilization in agriculture

Biochar is widely used in farmland, which is beneficial to soil carbon sequestration and promotes crop growth. Appropriate application of biochar can support both agricultural soil management and the net zero goal.

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Analyzing big data from biochar studies in China, Annette L. Cowie et, al. determined that biochar application can increase soil carbon sequestration by 35%, reduce soil CO_2 emission by about 33%, N_2O emissions by 23%, and increase crop yields by 11% [5]. And with the integrated pyrolysis and electricity generation (IPEG) system where biochar is 80% derived from crop residues, the reduction of net emissions from the planting industry would come to 902 Tg CO_2e annually, equivalent to 8.5% of China's national GHG emissions [5,11]. IPEG system can as well contribute to improving air quality with its replacement of crop residue combustion.

Ulfat et al. have found that the soil's capacity of carbon sequestration can be 2.5 Gt CO_2, a reduction of CO_2 emissions by 6.25% of the whole amount under a circularity measure that biochar can fix carbon while lowering GHG emission by increasing plant biomass because of improved soil conditions [12].

The effects of wheat straw and biochar addition on GHG emissions throughout two growing seasons (15 months) were researched by Hu et al. [13]. According to their findings, using biochar instead of applying biomass would result in lower emissions of CO_2 and N_2O. Mašek et al. reported that biochar modified with potassium can increase the carbon sequestration potential by 45%. This means this kind of biochar can contribute to the expected global biochar carbon sequestration potential of over 2.6 Gt CO_2-C(eq) annually [14]. In another case, Yang et al. applied biochar derived from corn residue to a corn field, resulting in the soil carbon sequestration increasing by 16% in the upper 15 cm soil and CH_4 emission decreased by 132% after 30 t ha^{-1} of the biochar was applied [15]. Additionally, the biochar amendment enhanced the corn yield by 7.4% over two years. This case indicated that biochar can also make contributions to mitigating GHG addition to CO_2 with the proper application of it.

When modifying biochar, pyrolysis temperature and aging play important roles. Yang et al. made biochar from maize straw through a series of processes at 300, 450, and 600 °C [16]. Then an incubation experiment using soils amended with/without fresh biochar and their equivalent aged samples was conducted next. They discovered that while aged samples showed the opposite trend and could be explained by the change from *Acidobacteriota* to *Proteobacteria*. Fresh samples produced at 450 °C and 600 °C significantly reduced soil carbon emissions because the biochar reduced dissolved organic matter (DOM) content. When it comes to the interaction of pyrolysis temperature and aging, the biochar produced under 450 °C and 600 °C can reduce soil CO_2 emission in the early stage, but with the biochar's aging in soil, the emission reduction effect of biochar is gradually weakened. In the soil treated by aging biochar, BC450 and BC600 which are produced under high temperatures promote soil CO_2 emission. This is mainly because the effects of biochar produced under high temperatures on soil dissolved organic carbon (DOC) content and soil bacterial community composition will change with the aging of biochar. Wang et al. have done a trial on aged biochar as well [17]. Their finding suggests that the possibility of lowering soil CO_2 and N_2O emissions may potentially increase due to aged biochar particles' presence of CO_2-fixing bacteria and restricted nitrification and ammonia oxidation. These results imply that aged biochar with increased soil physical stability could increase soil carbon sequestration and lower GHG emissions.

The carbon-nitrogen ratio and acid-alkalinity of soil affect the carbon sequestration ability of biochar. Iqbal et al. discovered that applying biochar or manure along with fertilizer caused emissions of CO_2 or N_2O [18]. The emissions of CO_2 and N_2O were highest for neutral and acidic soils with fertilizer but lowest for alkaline soils after applying biochar. The optimal performance to reduce GHGs is influenced by the carbon-nitrogen ratio of the soil: for a high carbon-nitrogen ratio, fertilizer or manure should be banned and biochar should be used instead. For soils with poor carbon-nitrogen ratios, however, combined biochar and fertilizer should be avoided.

The FeN_3-doped biochar demonstrated adequate adsorption capabilities for several GHGs in paddy fields (CH_4, CO_2, and N_2O) compared to pure biochar. This enhanced the adsorption energies to -1.37, -1.54, and -2.91 eV, respectively, and altered GHG molecule structure [19]. Additionally, the density of state and partial density of state analyses showed that the occurrence of a significant electron energy up- or down-shift of the electron for Fe *d*, C *p*, O *p*, or N *p* orbitals when CH_4, CO_2, or N_2O is adsorbed is what causes FeN_3-doped biochar to demonstrate exceptional adsorption capacity.

Table 1. Biochar's CCUS potential as an additive to soil.

Feedstock/ Modification	Reduction of GHG emission	Reference
Crop residues	33% soil CO_2, 23% soil N_2O	[5]
Potassium doped	Over 2.6 Gt CO_2-C(eq) per year	[14]
Corn residues	Carbon sequestration increased by 16%, 132% CH_4	[15]
Maize straw/Pyrolysis and aging	Significant reduction of CO_2	[16]
FeN_3-doped	Great absorption of CH_4, CO_2, or N_2O	[19]

Following the addition of biochar to the soil, there were changes in GHG emissions, including enhanced plant growth (which stores more carbon in vegetation), decreased non-CO_2 GHG emissions from the soil, and decreased mineralization of soil organic matter (Table 1).

2.2 Carbon utilization and storage as construction materials

Cement production, the most widely used building material on the planet, was responsible for 8% of all anthropogenic CO_2 emissions and 36% of CO_2 emissions from construction activities [20]. According to the *Cementing the European Green Deal*, it is acknowledged that 280 kg of CO_2 in each ton of cement cannot be removed during production and must be addressed through CCUS as shown in Figure 1 [21]. This highlights the importance of developing and implementing comprehensive strategies to reduce emissions across the entire value chain, including technical and non-technical solutions. Biochar can help take unprecedented steps to promote the use of carbon-negative building materials and innovate the design in order to meet the globally ambitious goal of net zero.

Integrating biochar into innovative biochar construction materials could facilitate waste valorization and reduce CO_2 emissions of construction materials [22]. In the most recent development, biochar, a carbon-negative substance, has been seen as a potentially successful replacement for cement and aggregate in building materials [23]. In the study of Wang et al., biochar derived from waste wood was added to cement-based composites, and CO_2 curing was performed [24]. For the manufacturing of composites, the CO_2 curing method effectively boosted carbonation compared to the air curing method. After carbonation, the plentiful cement hydrates strengthened the bonds, and the carbonates dense the microstructure, greatly enhancing the durability and carbon sequestration. Therefore, combining waste biochar and CO_2 curing to improve the qualities of cement-based composites and encourage waste recycling and CO_2 utilization could be a green technology.

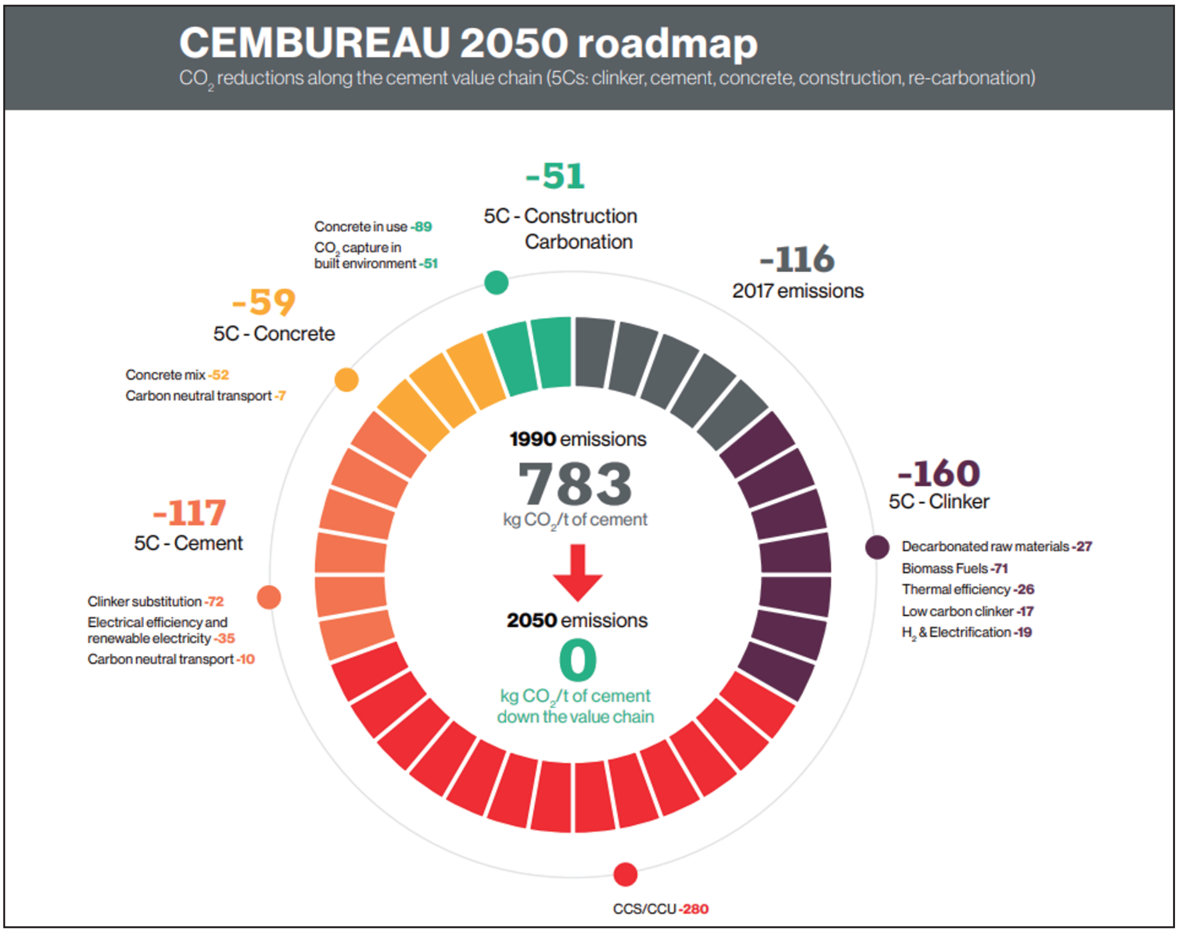

Fig. 1. CO_2 reductions along the cement value chain to align CEMBUREAU's 2050 roadmap with the European Green Deal's objectives, and deliver net zero [21]. 5Cs: clinker, cement, concrete, construction, re-carbonation.

(Source link: https://cembureau.eu/media/kuxd32gi/cembureau-2050-roadmap_final-version_web.pdf)

2.3 Absorbent for carbon capture

CO_2 adsorption capacity is controlled by specific surface area (SSA) and alkalinity while temperature should also be considered. The adsorption process is an overwhelming exothermic process, and the adsorption amount of CO_2 will be reduced with the increase in temperature. Straw and wood-based biochar performed well in carbon capture: Wood biochar had better CO_2 adsorption capacity (41.23–45.85 mg g^{-1}) than straw biochar (26.53–41.49 mg g^{-1}) due to the super pore structure [8]. Biochar derived from soybean straw showed the highest basicity and the highest carbon absorbing capacity among the straw biochar [8].

3 Conclusion

Despite variations in the total CO_2 reduction depending on many factors, widespread usage of biochar is usually regarded as effective for reducing emissions and achieving net zero emissions. This paper reviews the CCUS applications of biochar in three fields. In summary, biochar can play an essential role in CCUS including sequestrating carbon in the soil while promoting plants' growth simultaneously, being applied to construction material to store carbon and make good use of it, and absorbing carbon in the environment as a useful absorbent. However, potential drawbacks of biochar applications include the movement of biochar, contamination from biochar, detrimental changes to soil biology and characteristics, and negative effects on GHG emissions.

The lack of widespread use of biochar will be a stumbling block to achieving the goal of net zero. Society and the government need to pay more attention to the excellent performance of biochar in CCUS, eliminate economic difficulties, solve the problem of raw materials and preparation, and realize the large-scale application of biochar in CCUS as soon as possible.

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