The Role of Biochar in Enhancing Soil Carbon Sequestration for Carbon Neutrality

Jiayi Song*

Faculty of Social Sciences, University of Nottingham, NG9 2QL Nottingham, UK

Abstract. With the development of industry, carbon emissions are increasing: global temperatures are rising, habitats are shrinking, sea level rises and other issues are emerging one after another, climate change is getting more and more attention, and strategic goals such as carbon neutrality have also been formulated to alleviate global climate change. As a material to mitigate climate change and help achieve the goal of carbon neutrality, biochar can effectively absorb and store carbon and reduce carbon footprints. Through a critical analysis of the role of biochar in achieving carbon neutrality, this paper analyzes the principles of carbon absorption using biochar in agriculture, etc., and points out the existing limitations of biochar, such as high cost and land occupation, and efficacy instability, and gives the existing research based on the limitations. An increasing corpus of research has pinpointed elements like the temperature at which biochar is formed and the kind of biochar that is best for a certain soils and plants. Some solutions and mitigation methods conclude that biochar has a high development potential to help achieve carbon neutrality.

1 Introduction

The industrialization of human activities and the burning of large amounts of fossil fuels have had a huge impact on modern climate change by far. According to Thomas and Kevin's research, atmospheric carbon dioxide increased by 31% between 1961 and 1990 [1]. In addition, based on the uncertainty analysis, without policy mitigation, the 90% probability of temperature increase between 1990 and 2100 may be 1.7 °C to 4.9 °C. Rising atmospheric temperatures have led to rising sea levels, increased climate extremes, and a sharp decline in biodiversity, with serious negative impacts on the environment and human health. In order to alleviate this phenomenon, 195 member states of the United Nations signed the Paris Agreement in Paris in December 2015, controlling the trend of global warming within 1.5 °C above the pre-industrial level, and intending to slow down the trend of global warming. In order to accomplish this goal, the world must be carbon neutral, with subsequent negative emissions [2]. In total, 4.5% of the 198 nations that have committed to achieving carbon neutrality goals have already done so. Also, 120 out of 198 nations set a goal of achieving carbon neutrality by 2050–2070 [2]. A state of net-zero carbon dioxide emissions is known as carbon neutrality. It can be achieved by terminating emissions or negative carbon emissions to offset carbon dioxide in the atmosphere, such as using carbon sinks to store carbon, and industrial carbon capture. Biochar is a form of charcoal that is produced by heating organic material, such as wood, crop residues, or manure in the absence of oxygen through the pyrolysis process, in which the organic material is broken down and converted. Thus, a stable form of carbon is obtained, which can be stored for long periods of time, buffering the rate at which biochar is released into the atmosphere. Besides that, biochar can be used as a soil amendment to improve soil fertility, water retention, and nutrient cycling. In fact, since the slash-and-burn Palaeolithic epoch, biochar has been strongly associated with human civilization. According to Bezerra et al.'s research, Terra Preta, a biochar-like fertile soil in the Amazon Basin was discovered in 1879 and sparked discussion [3]. Despite the region's low soil quality and typically scarce food sources, civilization exists for a variety of reasons. Ancestors in Hemudu intentionally incorporated charcoal into the clay to decrease cohesiveness and enhance output of completed goods [4]. Due to climate change in modern times, biochar is gradually being used to mitigate the phenomenon of global warming and has played a certain role. According to estimates, a total of 376.11 MT CO2e of carbon might be sequestered in the soil using biochar [4]. It may assist India in lowering its emissions from agriculture and related activities by 41.41-63.26%. The application of biochar can help reduce carbon emissions in various types (Figure 1). In terms of climate change, biochar mainly works through 1: long-term storage of carbon in the soil; 2: as a renewable energy source to reduce carbon emissions in related energy sectors; 3: by improving soil fertility to reduce the production, use, and transportation of synthetic fertilizers in agriculture, and then reduce carbon emissions; 4: Since biochar can be generated from waste, it can reduce carbon emissions in practices such as landfill. In addition to combating climate change, biochar

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* Corresponding author: sgyjs3@nottingham.ac.uk

can reduce harmful substances in the environment due to the adsorption and sequestration of pollutants [5].

This article mainly critically explains the role of biochar in achieving carbon neutrality through the above four aspects of climate and give the limitations of biochar in carbon neutrality.

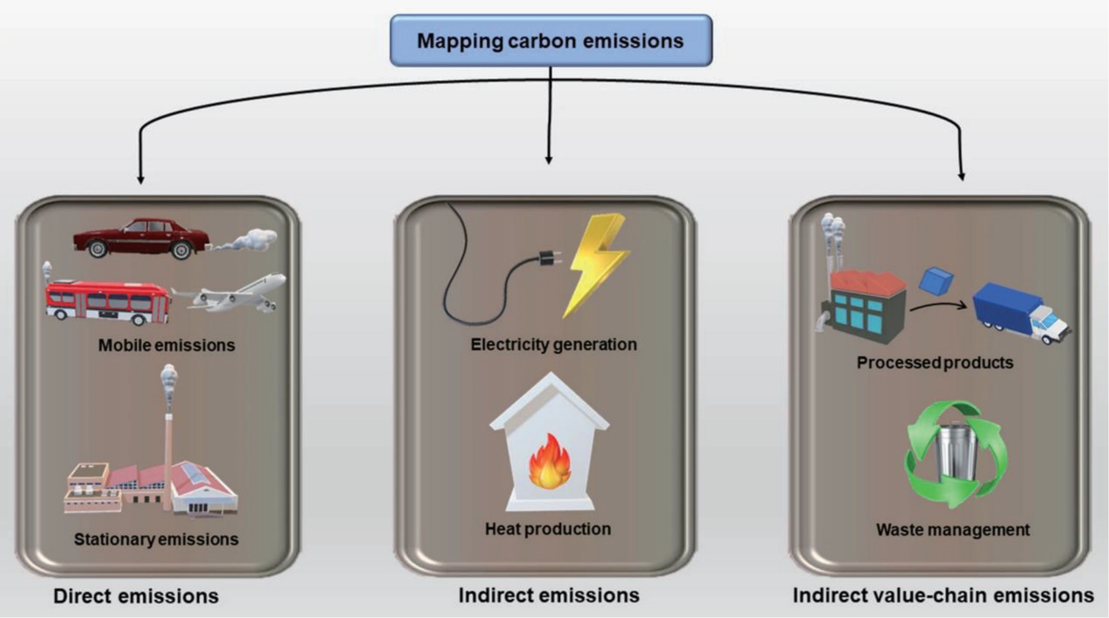

Fig. 1. Various types of carbon emissions [3].
(Source link: https://link.springer.com/article/10.1007/s10311-022-01435-8.)

2 Working principle

This section explains how biochar works by providing an analysis of its physical and chemical properties, including carbon sequestration and emission reductions.

2.1 Increase of soil carbon storage capability

Biochar can be used as a soil amendment to increase soil carbon storage through the following processes. Biochar itself is formed from biomass in the absence of oxygen and high temperature. One of the most common methods of biochar production is pyrolysis (Figure 2). Biomass is decomposed at 200-900 degrees Celsius in the absence of oxygen. Cellulose, lignin, and hemicellulose are the main components of biomass and are rich in carbon [6]. Therefore, this process involves the release of volatile substances such as oxygen and hydrogen and the separation of functional groups, so that the organic matter in the biomass is converted into stable aromatic carbon, which exists in the form of aromatic rings for a long time. The aromatic ring molecule is a ring structure composed of carbon atoms, in which the carbon-carbon bond is very stable and can exist on the earth for a long time, so it is not easy to be decomposed by microorganisms [7]. In addition, compared with other modifiers, biochar has the characteristics of long-term effective stability. Secondly, biochar can reduce carbon emissions by improving soil structure. When biochar is applied in the soil, it can promote the stable formation of soil aggregates, thereby alleviating the corrosion caused by factors such as geomantic omen. In addition to this, biochar has a large surface area and porous structure due to gas evolution due to biomass pyrolysis. When applied to the soil, it can play a role in water retention, providing water during droughts and floods, and absorbing water during floods, thereby reducing the probability of soil degradation and other hazards caused by uneven water distribution. The same goes for nutrients. The high affinity of carbon also leads to biochar can adsorb and retain a variety of nutrients and other substances [8].

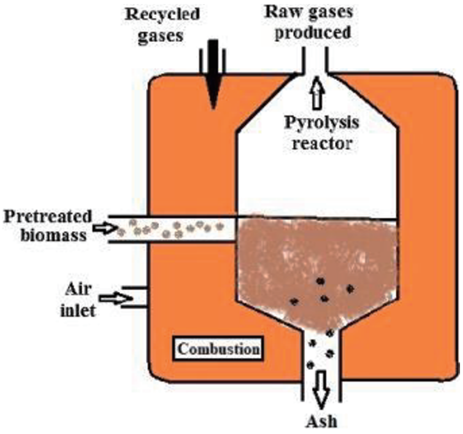

Fig. 2. Mechanism of pyrolysis [6].
(Source link:
https://www.sciencedirect.com/science/article/pii/S2215017X20300023.)

This structure of biochar provides a habitat for microorganisms in the soil, and accelerates the operation of the soil biological chain, improves biodiversity, and promotes nutrient cycling. The unique porous structure of biochar provides a shelter for microorganisms, and the formation of fungi and bacteria is conducive to the formation of a symbiotic relationship with specific plants, which is conducive to the growth of plants absorbing nutrients and the diversity of soil microbial groups, and then stores more plant biomass form of carbon. In addition, the soil modified by biochar is resistant to the pressure of surrounding environmental changes, which is conducive to the stability of the ecosystem. According to the research of Masto et al., who converted water hyacinth into biochar to manage weeds, soil microbial activity was significantly enhanced, respiration increased by 1.9 times, and biomass increased by 3 times [9]. Increased the richness of soil fungal bacteria. Soil microbes can convert plant leaves into more stable organic matter, such as corrosive substances, and can also reduce carbon leakage into the atmosphere in the form of carbon dioxide by incorporating carbon into soil particles [10].

2.2 Increase of fertility and water storage capacity

Biochar can be applied to soil as fertilizer to reduce carbon emissions. Biochar can reduce irrigation, synthetic fertilizer production, transportation and use, and thus reduce carbon emissions in agriculture by improving soil fertility. Soil cation exchange capability (CEC) is the absorption capacity of Mg, Ca, Na and other cations. The biochar structure can increase the soil CEC value and prevent the loss of them, then increase the content of soil nutrients. In addition, due to the characteristics of absorbing cations, adding biochar to soil can also hinder the circulation of toxic cations. Besides, because of reduced leaching and loss of nutrients and adsorption of harmful ions, it is also beneficial to prevent soil function, quality deterioration, nutrification in waterways, rivers, and reduce the need for costly water pollution treatment. Biochar can also change the pH of the soil. Biochar itself maintains a neutral pH. However, the high surface area and adsorptivity of biochar provide a site for ion exchange as well as adsorption. Therefore, when biochar is applied to soil, it acts as a buffer, increasing the concentration of hydrogen ions in alkaline soil and vice versa. In addition, specific soil pH can also improve the utilization of nutrients such as N and P by soil plants [11].

To sum up, biochar can increase soil fertility by increasing soil water storage capacity and utilization rate of nutrients, increasing soil microorganisms, etc., increasing the growth rate and growth rate of soil plants, thereby enhancing photosynthesis, and capturing carbon dioxide in the air. Therefore, biochar can effectively replace synthetic fertilizers in agriculture. An et al. based on a six-year field experiment concluded that adding 95% N, 89% P, 75% K, plus 1.5 t biochar per acre per year would increase rice yield by 6.6%, and plant root density, biomass and soil porosity compared to normal soil have significantly increased [12]. The study concluded that the application of biochar resulted in average reductions in carbon dioxide, methane and nitrous oxide levels of 22%, 132%, and 68%, respectively, compared with the control group. These results were attributed to the carbon storage capacity of biochar (as a long-term carbon sink) and the improvement of soil properties by biochar, respectively. In addition to this, maize yield increased by 7.4% in two years, and soil organic carbon (SOC) sequestration in the upper 15-cm depth increased by 16% after biochar amendment (30 t ha^{-1}) [13]. Fast pyrolysis of rice husk would provide biochar with an energy value of roughly 560 USD/T, which is much less expensive than the price of traditional fuel [14]. This could reduce the carbon emissions from fertilizer production, use and transportation. In addition, due to the reduction of leaching and loss of nutrients and the adsorption of harmful ions, it is also beneficial to prevent the neutralization of waterways and rivers, and reduce the need for expensive water pollution treatment. According to Xu et al.'s research, unlike the same charcoal produced from wildfires, which had a favourable influence on plant development, laboratory-made charcoal from Douglas-fir and Ponderosa Pine (Pinus ponderosa) had a detrimental impact on plant growth [5]. In addition, since biochar is produced from renewable sources, such as organic materials such as agricultural and forestry waste, it can be used as clean energy, releasing energy in the form of gasification, combustion, etc., for power generation or building manufacturing. Since biochar emits less greenhouse gases than traditional fuels such as petroleum and coal, it has a smaller carbon footprint. Therefore, it can be used as an effective alternative energy source to reduce carbon emissions in the energy sector and traditional waste treatment such as landfill. When biochar was employed in landfill cover engineering, CH_4 removal rates rose from around 60 to 90% [15].

3 Limitations of biochar

First of all, in terms of production, the large-scale production of biochar requires a large amount of raw materials, which is characterized by high cost. There may be potential environmental problems in the production and development of biochar raw material biomass. For example, converting forests to energy crops may affect biological habitats and soil health, with resources negatively impacted. In addition, the transportation of biomass and the pyrolysis process of biomass also lead to greenhouse gas emissions [14].

Biochar may not be suitable for all soils, depending on soil properties such as pH, texture, nutrients, etc. according to Mosa et al.'s research, the biochar's' N2O reduction indices varied depending on the feedstock Field crop husks (0.47%) are followed by hardwood (18.1%), field crop husks (27.1%), manures (27.0%), and bamboo (31.9%) [16]. Second, the effectiveness and stability of carbon storage in biochar depends on the biomass feedstock and the method used to convert biomass into biochar such as residence time and heating rate. It has been suggested that the temperature rise in high temperature pyrolysis will lead to shrinkage of the solid structure and reduce the pore density of biochar. The temperature of pyrolysis is generally 200-400 degrees Celsius, but small temperature changes in this range have a great impact on the characteristics of biochar [8]. Finally, although biochar can sequester carbon based on its aromatic structure, the evidence for long-term carbon storage remains incomplete, and there is no exact storage time to record the release of stored carbon back into the atmosphere. Over time, once carbon saturation is reached, the carbon storage capacity of biochar may weaken and may be affected by factors such as soil type and biochar species. According to Ning et al.'s research, high input of biochar reduced rice yield and damaged soil health [12].

4 Improvements

However, choosing raw materials that are easy to mine and have high carbon content and optimized production methods, and formulating special pyrolysis temperatures for different plant types, can improve the carbon storage capacity of biochar. A growing body of research crystallizes biochar applications, according to different vegetation and soil types, the most suitable biochar raw material types, production methods and application rates are obtained. Studies have proven that water hyacinth biochar works best at 300-350 °C and a residence time of 30-40 minutes [7]. By mimicking rainstorm events, 1% or 3% biochar can lessen the rate of soil loss compared to 7% biochar addition that causes soil loss [14].

According to Amin et al.'s study, many techniques have been developed for more efficient qualitative and quantitative analysis of biochar such as spectroscopic techniques including X-ray photoelectron spectroscopy, X-ray diffraction, Solid-state NMR spectroscopy, etc [17]. Combined with quantitative analysis methods, the effect of biochar on vegetation soil microorganisms can be more accurately understood for long-term benefits. In addition, the carbon in the biochar production process can be selectively separated by capture technology such as CTO-375. Another method is microwave pyrolysis of biomass. Compared with traditional biomass pyrolysis, microwave pyrolysis of biomass can convert biomass wastes into three different multipurpose goods Such as solid biochar, liquid bio-oil, and syngas, through thermochemistry, which has lower cost with higher productivity [11].

In addition, the evaluation of biochar application is also very important. The cost and social evaluation of biochar application implementation are compared with possible risks such as river acidification and triplication, so that the use of biochar can be more tailored to local conditions [14]. In addition, LCA is a method for assessing the effectiveness of biochar: Target definition and scope, life cycle inventory analysis, life cycle impact assessment, and interpretation, which determining biochar effectiveness [14]. Furthermore, combining biochar with other carbon storage methods as well as land use policies such as afforestation and other soil amendments can further increase the carbon storage potential. In terms of cost, you can choose relatively cheap raw materials and economic policy support.

5 Conclusion

This paper analyzes the production of biochar (waste utilization) and its application in agriculture, waste management, etc., and concludes that biochar can effectively store carbon and reduce carbon footprint. However, due to the variety of biochars and the uncertainty of their production, the produced biochars vary depending on the precise temperature in the pyrolysis process. In addition to that, the availability of biochar also varies with soil properties and vegetation types. In addition, there may be additional carbon emissions or negative environmental impacts during the production, production and transportation of biochar. In response to the above limitations, there are some specific temperatures for specific vegetation soils, and biomass raw materials can improve the efficiency of biochar in a targeted manner. In general, biochar is of great significance in achieving global carbon neutrality, and more research methods are still needed to reduce the uncertainties in the still existing production, transportation, and environmental interactions.

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