Potential of Biochar to Sequester Carbon and Mitigate Greenhouse Gas Emissions.

Abstract:

Biochar is a solid material obtained from the carbonization of any biomass including weeds, crop residues and other wastes of plant origin. Biochar has a significant role in climate change mitigation through sequestration of carbon in the soil and reduction of nitrous oxide (N_2O) and methane (CH_4) gas emissions to atmosphere by improving uptake of the soil. Here we review the potential of biochar to reduce N_2O and CH_4 emissions from agricultural practices and sequester atmospheric CO_2 in the soil including potential mechanism behind observed effects. However, some fundamental mechanism and manipulation of biochar remain understandable and need further investigation.

Introduction:

Global warming (GW) is the rise in the average earth surface temperature as a result of increase in the concentration of greenhouse gases (GHGs) including methane (CH_4), nitrous oxide (N_2O), water vapor, ozone (O_3), chlorofuorocarbons (CFCs) and carbon dioxide (CO_2) (Al-Ghussain 2019). One of the most pervasive GHGs is CH_4, which is released from wetlands, paddy fields, coal mines, ruminants, and human activities including rearing livestock and natural gas leakage (Waqas et al. 2020). Continuous anthropogenic greenhouse gas (GHG) emissions, such as CO_2, CH_4, and N_2O have been identified as the primary cause of today's climate change [Montzka et al., 2011]. According to data estimated by the United States Environmental Protection Agency (USEPA) in 2020, agricultural operations accounted for a considerable share of overall GHG emissions (about 11%), owing primarily to inadequate soil management techniques [USEPA, 2022]. Biochar has been widely reported as a promising substance for reducing GHG emissions, particularly CH_4 emissions from paddy land (Awad et al. 2018; Han et al. 2016; Wu et al. 2019a). Furthermore, a meta-analysis on biochar found that applying various forms of biochar to soil significantly reduces CH_4 emissions (Awad et al. 2018). These findings imply that the environmental benefit of biochar application on CH_4 emissions has been widely shown. Biochar is a fine-grained, carbon-rich, porous substance that remains after plant biomass has been thermochemically converted (pyrolyzed) at low temperatures (350-600°C) in an oxygen-depleted environment (Amonette and Joseph, 2009). Biochar increases soil's physical (e.g., water holding capacity, O_2 content, and moisture level), chemical (e.g., pollutant immobilisation and carbon sequestration), and biological (e.g., microbial abundance, variety, and activity) (Gul et al., 2015). These biochar properties eventually contribute to soil carbon sequestration (Windeatt et al., 2014), as well as reduced greenhouse gas (GHG) emissions (Stewart et al., 2013). Furthermore, it has been suggested that using biochar as a soil addition could help slow down climate change by long-term carbon sequestration while also enhancing the characteristics and capabilities of soil (Jeffery et al., 2011; Kookana et al., 2011; Verheijen et al., 2010). Zhang et al. (2010) also revealed that biochar amendment results in lower methane and nitrous oxide emissions from agricultural soils, which helps to mitigate the consequences of climate change.

Moreever, biochar characteristics and soil management practises have the potential to lower N_2O emissions by up to 80%. (Wang et al., 2013). The postulated mechanisms include N_2O trapping in watersaturated soil pores and microbial activity associated with biological denitrification, both of which would reduce the $N_2O/(N_2O + N_2)$ ratio (Harter et al., 2016). It is believed that the intensive use of nitrogen fertilisers in agriculture was responsible for two-thirds of the N_2O emissions (Cayuela et al., 2014; Laird et al., 2011). As a result, the application of biochar may limit N availability to crops, reducing N losses through direct and indirect N_2O emissions while enhancing crop output (Wang et al., 2013). The use of chemical fertiliser in conjunction with biochar is an innovative method that contributes to climate change mitigation, lowers chemical fertiliser application rates, increases crop production, and improves water retention, all of which contribute to more sustainable agriculture (Wang et al., 2015).

Biochar C sequestration and greenhouse gas emission reduction

Carbon dioxide (CO_2) emissions from the usage of fossil fuels are widely recognized as the primary cause of climate change (El-Naggar et al. 2019). Capturing this atmospheric carbon can help to reduce rising greenhouse gas emissions. Large amounts of biochar can be utilized to store carbon in the agriculture sector (El-Naggar et al. 2019). This makes biochar appealing as a carbon sequestration option, in addition to its potential for improving soil quality and reducing pollution emission (Clough and Condron 2010). Climate change mitigation through carbon sequestration is significant biochar application apart from improved crop yield (Sohi et al., 2010; Majumder et al., 2019). The application of biochar has the potential to sequester carbon due to the high stability of C compounds created during biomass pyrolysis (Forbes et al. 2006) and their consequent slow decomposition in soil (Sohi et al. 2009). Soil carbon (C) sequestration through biochar amendment has been proposed as an effective countermeasure for the rising concentration of atmospheric GHGs (Pan et al., 2004; Smith et al., 2008). The recalcitrant nature of biochar draws carbon from the atmosphere, providing a carbon sink to terrestrial ecosystems whilst improving water and soil quality (Lehmann et al., 2009). Reducing N_2O and CH_4 emissions as a result of biochar application is gaining a lot of interest because these gases have far higher global warming potentials than CO_2 (Steiner et al., 2008; Rogovska et al., 2008). Biochar can play a larger role in short-term CH_4 emission reduction to assist meet the 2050 GHG targets because methane's GWP20 (for a 20-year time horizon) value of 84 is substantially higher than its GWP100 due to its short residence duration in the atmosphere (Balcombe et al., 2018). Soils are responsible for over 62% of the atmospheric N_2O emissions (Biernat et al., 2020). The application of nitrogen-based fertiliser to fields at high rates emits N_2O into the environment. Biochar addition to soil effectively reduces soil N_2O emissions, and the reduction can be attributable to the suppression of either the nitrification or denitrification stages, as observed in both field and laboratory investigations (Rondon et al., 2007; Cayuela et al., 2014; Weldon et al., 2019). The use of biochar can also reduce direct and indirect greenhouse gas emissions by retaining nitrogen in soils and reducing the need for synthetic fertilizer inputs to produce crop yields, increasing crop productivity per unit land area, and possibly requiring less energy to irrigate due to improved soil water retention capacities (Woolf et al. 2010). These biochar characteristics eventually contribute to soil carbon sequestration (Windeatt et al., 2014), greenhouse gases (GHGs) emission reduction (Stewart et al., 2013), and therefore contribute to an overall improvement in soil health (Zhang et al., 2013).

Biochar Mitigates N_2O Emission

Nitrous oxide (N_2O) is one of the most potent greenhouse gases put into the atmosphere, with 298 times the global warming potential of carbon dioxide (CO_2) (Ravishankara et al. 2009, Canfield et al. 2010). Agriculture soils are responsible for 60% of anthropogenic N_2O emissions due to the widespread use of synthetic nitrogen fertilisers and inadequate management of livestock excreta (Reay et al. 2012, Lopez-Aizpun et al. 2020). In soil, N_2O is created and consumed through a variety of separate but interconnected processes, including specialised abiotic redox reactions and three major biotic processes (nitrification, denitrification, and nitrifier denitrification) (Zhu et al. 2013, Butterbach-Bahl et al. 2013, Sgouridis et al. 2015). Despite the fact that these processes may co-occur and exhibit considerable geographical and temporal variability, inadequate denitrification is widely regarded as the major cause of N_2O emissions in agricultural soils (Butterbach-Bahl and Dannenmann 2011, Zheng and Doskey 2015). Biochar has been widely reported to impact N_2O emissions from the denitrification pathway as a promising soil amendment (Cayuela et al. 2014). The majority of recent research has been on the impacts of biochar on soil denitrification kinetics and functional potentials at the community level (Su et al. 2019, Harter et al. 2014). Biochar addition may have an indirect effect on denitrifying kinetics and abundance by modifying moisture content, pH, air permeability, nutrient bioavailability, and even nitrification. Furthermore, the effect of biochar amendment on soil physicochemical properties varied depending on soil primary conditions and the nature of biochars, as well as the structures, compositions, dosages, and surface properties of biochars made with different precursors at different pyrolysis temperatures (Haider et al. 2017, Luo et al. 2020, Su et al. 2019). Biochar has the potential to reduce N_2O emissions by blocking the conversion of nitrate or nitrite to N_2O (Chen et al. 2018), and it has the potential to directly drive the microbial conversion of N_2O to nitrogen gas (Liu et al. 2019, Xu et al. 2014).

Biochar Mitigates CO_2 Emission

Carbon dioxide (CO2), a powerful greenhouse gas (GHG), is to blame for global climate change as its concentration in the atmosphere rises. Intensive agriculture is one source of GHG emissions (Melillo and Morrisseau 2002). The addition of biochar has been shown to change soil porosity, moisture content, pH, labile C and N pool sizes, all of which have a significant impact on soil CO_2 emissions (Sohi et al. 2010, Stavi and Lal 2013). Previous research, however, has shown that biochar addition with different source materials and soil textures can have varying impacts (an increase, a decrease, or no effect) on CO_2 flow in laboratory or field trials (Novak et al. 2010, Scheer et al. 2011, Wang et al. 2014). Furthermore, when biochar addition increased, CO_2 emissions decreased (Prayogo et al. 2013), which may be attributed to the sorption of labile

C onto the surface or into the pores of biochar (Lehmann et al. 2011). Several studies have found a reduction in CO_2 emissions from biochar-amended soil with N addition (Iqbal et al. 2009, Zimmerman et al. 2011). It was also discovered that when N fertiliser was given to the soil in the presence of biochar, total CO_2 emissions reduced (Zhang et al. 2012). The addition of biochar has the ability to offset total CO_2 emissions caused by N fertiliser (Shen et al. 2017). Thus, although the addition of biochar tended to increase the total amount of CO_2 over time in the short term (Zhang et al. 2010), it would be an effective strategy to reduce GHG emissions caused by the use of N fertiliser and could prevent long-term C sequestration as a relatively resistant C source in soil (Lehmann et al. 2011).

Biochar Mitigates CH_4 Emission

Atmospheric methane (CH_4) is recognized as a key greenhouse gas contributing to global climate change, with a global warming potential 34 times that of carbon dioxide over a 100-year time frame, and its worldwide mean concentration has increased by 2.5 times since the pre-industrial era (IPCC, 2013). Paddy soils are the most significant human source of CH_4 emissions (Wang et al., 2018a). Rice cultivation generated roughly 500 Mt CO_2 eq to world CH_4 emissions in 2011, and it is anticipated to increase by 7% by 2030 and another 6% by 2050 (FAO, 2014). Biochar treatment in rice agriculture has previously been shown to reduce CH_4 emissions by 33.8-91% (Xiao et al. 2018, Knoblauch et al. 2011, Wang et al. 2019). Its distinct characteristics can also improve soil parameters, particularly those relating to soil fertility (Lehmann and Rondon, 2006). In terms of reducing CH_4 emissions, biochar encouraged more CH_4 oxidation than CH_4 generation in rice fields (Qin et al., 2016; Singh and Seneviratne, 2017; Wang et al., 2018b). Previous research has revealed that these phases of rice growth coincide with active CH_4 oxidation activity by aerobic CH_4-oxidizing bacteria (methanotrophs) (Van and Nehu, 1996; Jia et al., 2001). Han et al. (2016) also demonstrated that biochar could increase methanotroph activity, resulting in increased CH_4 oxidation. Biochar, with its porous structure that provides a habitat and oxygen availability, can promote bacterial growth, particularly aerobes (Qin et al., 2016; Chen et al., 2017). Because methane oxidation occurs in the rhizosphere, where oxygen is abundant, enhanced rice growth under biochar conditions may also offer additional oxygen for this process (Wassmann et al., 2000). According to Feng et al. (2012) and Wang et al. (2019) reduced CH_4 emissions can be explained by a decrease in the ratio of methanogens to methanotrophs, showing that biochar application inhibits methanogen growth while promoting methanotrophic growth. Hence, the participation of biochar in lowering CH_4 generation and increasing its oxidation are the two main explanations for the lower emissions attained by employing biochar. Feng et al. (2012) and Chen et al. (2018) also found a decrease in CH_4 fux after applying biochar to paddy soils, implying that the effects of biochar on CH_4 emission were long-lasting. Huang et al. (2019) discovered that biochar addition reduced CH_4 emissions, which might be attributed to lower methanogenic archaea abundance; thus, CH_4 could be consumed by methanotrophs.

Conclusion:

This review collects available data on sequestration of Carbon and mitigating climate change by reducing the emissions of greenhouse gases (CH_4, N_2O, CO_2) in agricultural fields through use of biochar in soil, insight of the key processes involved, offers mechanisms of some of the key processes. We suggest that further studies are needed to assess the complete effect of different biochar application on mitigation of climate change.

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