

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 (N₂O) and methane (CH₄) gas emissions to atmosphere by improving uptake of the soil. Here we review the potential of biochar to reduce N₂O and CH₄ emissions from agricultural practices and sequester atmospheric CO₂ 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 (CH₄), nitrous oxide (N₂O), water vapor, ozone (O₃), chlorofluorocarbons (CFCs) and carbon dioxide (CO₂) (Al-Ghussain 2019). One of the most pervasive GHGs is CH₄, 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 CO₂, CH₄, and N₂O 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 CH₄ 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 CH₄ emissions (Awad et al. 2018). These findings imply that the environmental benefit of biochar application on CH₄ 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, O₂ 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

Comment [A1]: Please specific on what is the uptake improvement u mean? Nutrient/water?

Comment [A2]: Soil amendment

revealed that biochar amendment results in lower methane and nitrous oxide emissions from agricultural soils, which helps to mitigate the consequences of climate change.

Moreover, biochar characteristics and soil management practises have the potential to lower N₂O emissions by up to 80%. (Wang et al., 2013). The postulated mechanisms include N₂O trapping in watersaturated soil pores and microbial activity associated with biological denitrification, both of which would reduce the N₂O/(N₂O + N₂) ratio (Harter et al., 2016). It is believed that the intensive use of nitrogen fertilisers in agriculture was responsible for two-thirds of the N₂O 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 N₂O 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).

Comment [A3]: However, high pH of biochar could increase ammonia volatilization..The authors are required to get comparison of multiple studies in order to provide insights on this context.

Biochar C sequestration and greenhouse gas emission reduction

Carbon dioxide (CO₂) 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 gasemissions.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 N₂O and CH₄ emissions as a result of biochar application is gaining a lot of interest because these gases have far higher global warming potentials than CO₂ (Steiner et al., 2008; Rogovska et al., 2008).Biochar can play a larger role in short-term CH₄ 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 N₂O emissions (Biernat et al., 2020).The application of nitrogen-based fertiliser to fields at high rates emits N₂O into the environment. Biochar addition to soil effectively reduces soil N₂O 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

Comment [A4]: Avoid using obsolete references, particularly in review article.

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 N₂O Emission

Nitrous oxide (N₂O) is one of the most potent greenhouse gases put into the atmosphere, with 298 times the global warming potential of carbon dioxide (CO₂) (Ravishankara et al. 2009, Canfield et al. 2010). Agriculture soils are responsible for 60% of anthropogenic N₂O 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, N₂O 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 N₂O emissions in agricultural soils (Butterbach-Bahl and Dannenmann 2011, Zheng and Doskey 2015). Biochar has been widely reported to impact N₂O 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 N₂O emissions by blocking the conversion of nitrate or nitrite to N₂O (Chen et al. 2018), and it has the potential to directly drive the microbial conversion of N₂O to nitrogen gas (Liu et al. 2019, Xu et al. 2014).

Biochar Mitigates CO₂ 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 CO₂ 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 CO₂ flow in laboratory or field trials (Novak et al. 2010, Scheer et al. 2011, Wang et al. 2014). Furthermore, when biochar addition increased, CO₂ 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

Comment [A5]: Besides the biochar condensed C and its recalcitrant characteristics help to sequester C, what are the other characteristic would help to sequester C too? How about its physical characteristics? In-depth study of literature on the biochar characteristics is needed to improve this review paper.

a reduction in CO₂ 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 CO₂ emissions reduced (Zhang et al. 2012). The addition of biochar has the ability to offset total CO₂ emissions caused by N fertiliser (Shen et al. 2017). Thus, although the addition of biochar tended to increase the total amount of CO₂ 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).

Comment [A6]: Lack of information on mechanism in CO₂ emission from biochar-amended soil with N fertilization. Is the chemical /physical characteristics of biochar resulting in reduction of CO₂ emission?

Biochar Mitigates CH₄ Emission

Atmospheric methane (CH₄) 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 CH₄ emissions (Wang et al., 2018a). Rice cultivation generated roughly 500 MtCO₂eq to world CH₄ 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 CH₄ 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 CH₄ emissions, biochar encouraged more CH₄ oxidation than CH₄ 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 CH₄ oxidation activity by aerobic CH₄-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 CH₄ 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 CH₄ 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 CH₄ 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 CH₄ flux after applying biochar to paddy soils, implying that the effects of biochar on CH₄ emission were long-lasting. Huang et al. (2019) discovered that biochar addition reduced CH₄ emissions, which might be attributed to lower methanogenic archaea abundance; thus, CH₄ 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 (CH₄, N₂O, CO₂) 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.

References:

Al-Ghussain L. Global warming: review on driving forces and mitigation. *Environ Prog Sustain Energy*. 2019;38:13–21.

Amonette JE, Joseph S. Characteristics of biochar: microchemical properties. In *Biochar for environmental management 2012*; pp. 65-84.

Amonette, J. and Joseph, S. 2009. Characteristics of biochar: Micro-chemical properties. In: *Biochar for environmental management: Science and technology* (J. Lehmann and S. Joseph, eds.). Earth Scan, London. pp 33-52.

Awad YM, Wang J, Igalavithana AD, Tsang DCW, Kim K-H, Lee SS et al. Chapter One—biochar effects on rice paddy: metaanalysis. In: Sparks DL (ed) *Advances in agronomy*. Academic Press, 2018; pp 1–32.

Balcombe P, Speirs JF, Brandon NP, Hawkes AD. Methane emissions: choosing the right climate metric and time horizon. *Environmental Science: Processes & Impacts*. 2018;20(10):1323-39.

Biernat L, Taube F, Loges R, Kluß C, Reinsch T. Nitrous oxide emissions and methane uptake from organic and conventionally managed arable crop rotations on farms in Northwest Germany. *Sustainability*. 2020;12(8):3240.

Butterbach-Bahl K, Baggs EM, Dannenmann M, Kiese R, Zechmeister-Boltenstern S. Nitrous oxide emissions from soils: how well do we understand the processes and their controls?. *Philosophical Transactions of the Royal Society B: Biological Sciences*. 2013;368(1621):20130122.

Butterbach-Bahl K, Dannenmann M. Denitrification and associated soil N₂O emissions due to agricultural activities in a changing climate. *Current Opinion in Environmental Sustainability*. 2011;3(5):389-95.

Canfield DE, Glazer AN, Falkowski PG. The evolution and future of Earth's nitrogen cycle. *science*. 2010;330(6001):192-6.

Cayuela ML, Van Zwieten L, Singh BP, Jeffery S, Roig A, Sánchez-Monedero MA. Biochar's role in mitigating soil nitrous oxide emissions: A review and meta-analysis. *Agriculture, Ecosystems & Environment*. 2014;191:5-16.

- Chen D, Wang C, Shen J, Li Y, Wu J. Response of CH₄ emissions to straw and biochar applications in double-rice cropping systems: Insights from observations and modeling. *Environmental Pollution*. 2018;235:95-103.
- Chen G, Zhang Z, Zhang Z, Zhang R. Redox-active reactions in denitrification provided by biochars pyrolyzed at different temperatures. *Science of the Total Environment*. 2018;615:1547-56.
- Chen J, Li S, Liang C, Xu Q, Li Y, Qin H, Fuhrmann JJ. Response of microbial community structure and function to short-term biochar amendment in an intensively managed bamboo (*Phyllostachys praecox*) plantation soil: effect of particle size and addition rate. *Science of the Total Environment*. 2017;574:24-33.
- Clough TJ, Condon LM. Biochar and the nitrogen cycle: introduction. *Journal of environmental quality*. 2010;39(4):1218-23.
- El-Naggar A, El-Naggar AH, Shaheen SM, Sarkar B, Chang SX, Tsang DC, Rinklebe J, Ok YS. Biochar composition-dependent impacts on soil nutrient release, carbon mineralization, and potential environmental risk: a review. *Journal of environmental management*. 2019;241:458-67.
- Feng Y, Xu Y, Yu Y, Xie Z, Lin X. Mechanisms of biochar decreasing methane emission from Chinese paddy soils. *Soil Biology and Biochemistry*. 2012;46:80-8.
- Forbes MS, Raison RJ, Skjemstad JO. Formation, transformation and transport of black carbon (charcoal) in terrestrial and aquatic ecosystems. *Science of the total environment*. 2006;370(1):190-206.
- Gul S, Whalen JK, Thomas BW, Sachdeva V, Deng H. Physico-chemical properties and microbial responses in biochar-amended soils: mechanisms and future directions. *Agriculture, Ecosystems & Environment*. 2015;206:46-59.
- Haider G, Steffens D, Moser G, Müller C, Kammann CI. Biochar reduced nitrate leaching and improved soil moisture content without yield improvements in a four-year field study. *Agriculture, Ecosystems & Environment*. 2017;237:80-94.
- Han X, Sun X, Wang C, Wu M, Dong D, Zhong T, Thies JE, Wu W. Mitigating methane emission from paddy soil with rice-straw biochar amendment under projected climate change. *Scientific reports*. 2016;6(1):24731.
- Harter J, Guzman-Bustamante I, Kuehfuss S, Ruser R, Well R, Spott O, Kappler A, Behrens S. Gas entrapment and microbial N₂O reduction reduce N₂O emissions from a biochar-amended sandy clay loam soil. *Scientific Reports*. 2016;6(1):1-5.
- Harter J, Krause HM, Schuettler S, Ruser R, Fromme M, Scholten T, Kappler A, Behrens S. Linking N₂O emissions from biochar-amended soil to the structure and function of the N-cycling microbial community. *The ISME journal*. 2014;8(3):660-74.

Huang Y, Wang C, Lin C, Zhang Y, Chen X, Tang L, Liu C, Chen Q, Onwuka MI, Song T. Methane and nitrous oxide flux after biochar application in subtropical acidic paddy soils under tobacco-rice rotation. *Scientific reports*. 2019;9(1):17277.

IPCC. *Climate Change 2013: the Physical Science Basis: Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, New York. 2013;1535.

Iqbal J, Hu R, Lin S, Hatano R, Feng M, Lu L, Ahamadou B, Du L. CO₂ emission in a subtropical red paddy soil (Ultisol) as affected by straw and N-fertilizer applications: A case study in Southern China. *Agriculture, Ecosystems & Environment*. 2009;131(3-4):292-302.

Jeffery S, Verheijen FG, van der Velde M, Bastos AC. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agriculture, ecosystems & environment*. 2011;144(1):175-87.

Jia Z, Cai Z, Xu H, Li X. Effect of rice plants on CH₄ production, transport, oxidation and emission in rice paddy soil. *Plant and soil*. 2001;230:211-21.

Knoblauch C, Maarifat AA, Pfeiffer EM, Haefele SM. Degradability of black carbon and its impact on trace gas fluxes and carbon turnover in paddy soils. *Soil Biology and Biochemistry*. 2011;43(9):1768-78.

Kookana RS, Sarmah AK, Van Zwieten L, Krull E, Singh B. Biochar application to soil: agronomic and environmental benefits and unintended consequences. *Advances in agronomy*. 2011;112:103-43.

Laird DA, Rogovska NP, Garcia-Perez M, Collins HP, Streubel JD, Smith M. Pyrolysis and biochar—opportunities for distributed production and soil quality enhancement. *Insustainable alternative fuel feedstock opportunities, challenges and roadmaps for six US regions, in proceedings of the sustainable feedstocks for advanced biofuels workshop 2011* (pp. 257-281).

Lehmann J, Rillig MC, Thies J, Masiello CA, Hockaday WC, Crowley D. Biochar effects on soil biota—a review. *Soil biology and biochemistry*. 2011;43(9):1812-36.

Lehmann J, Rondon M. Bio-char soil management on highly weathered soils in the humid tropics. *Biological approaches to sustainable soil systems*. 2006;113(517):e530.

Liu Q, Liu B, Zhang Y, Hu T, Lin Z, Liu G, Wang X, Ma J, Wang H, Jin H, Ambus P. Biochar application as a tool to decrease soil nitrogen losses (NH₃ volatilization, N₂O emissions, and N leaching) from croplands: Options and mitigation strength in a global perspective. *Global Change Biology*. 2019;25(6):2077-93.

Lopez-Aizpún M, Horrocks CA, Charteris AF, Marsden KA, Ciganda VS, Evans JR, Chadwick DR, Cárdenas LM. Meta-analysis of global livestock urine-derived nitrous oxide emissions from agricultural soils. *Global change biology*. 2020;26(4):2002-13.

- Luo J, Lin L, Liu C, Jia C, Chen T, Yang Y, Shen M, Shang H, Zhou S, Huang M, Wang Y. Reveal a hidden highly toxic substance in biochar to support its effective elimination strategy. *Journal of hazardous materials*. 2020;399:123055.
- Melillo JM, Steudler PA, Aber JD, Newkirk K, Lux H, Bowles FP, Catricala C, Magill A, Ahrens T, Morrisseau S. Soil warming and carbon-cycle feedbacks to the climate system. *Science*. 2002;298(5601):2173-6.
- Montzka SA, Dlugokencky EJ, Butler JH. Non-CO₂ greenhouse gases and climate change. *Nature*. 2011;476(7358):43-50.
- Novak JM, Busscher WJ, Watts DW, Laird DA, Ahmedna MA, Niandou MA. Short-term CO₂ mineralization after additions of biochar and switchgrass to a TypicKandiudult. *Geoderma*. 2010;154(3-4):281-8.
- Pan GX, Li LQ, Wu LS, Zhang XH. Storage and sequestration potential of topsoil organic carbon in China's paddy soils. *Global Change Biology*. 2004;10:79-92.
- Prayogo C, Jones JE, Baeyens J, Bending GD. Impact of biochar on mineralisation of C and N from soil and willow litter and its relationship with microbial community biomass and structure. *Biology and Fertility of Soils*. 2014;50:695-702.
- Qin X, Wang H, Liu C, Li J, Wan Y, Gao Q, Fan F, Liao Y. Long-term effect of biochar application on yield-scaled greenhouse gas emissions in a rice paddy cropping system: A four-year case study in south China. *Science of the Total Environment*. 2016;569:1390-401.
- Qin X, Wang H, Liu C, Li J, Wan Y, Gao Q, Fan F, Liao Y. Long-term effect of biochar application on yield-scaled greenhouse gas emissions in a rice paddy cropping system: A four-year case study in south China. *Science of the Total Environment*. 2016;569:1390-401.
- Ravishankara AR, Daniel JS, Portmann RW. Nitrous oxide (N₂O): the dominant ozone-depleting substance emitted in the 21st century. *science*. 2009;326(5949):123-5.
- Reay DS, Davidson EA, Smith KA, Smith P, Melillo JM, Dentener F, Crutzen PJ. Global agriculture and nitrous oxide emissions. *Nature climate change*. 2012;2(6):410-6.
- Rogovska NP, Fleming P, Laird DA, Cruse RM, Parkin T, Meek D. Biochar influences on greenhouse gas emissions from a Midwestern Agricultural soil. *Soil Sci. Soc. Am. J.* (submitted). 2010.
- Rondon MA, Lehmann J, Ramírez J, Hurtado M. Biological nitrogen fixation by common beans (*Phaseolus vulgaris* L.) increases with bio-char additions. *Biology and fertility of soils*. 2007;43:699-708.
- Scheer C, Grace PR, Rowlings DW, Kimber S, Van Zwieten L. Effect of biochar amendment on the soil-atmosphere exchange of greenhouse gases from an intensive subtropical pasture in northern New South Wales, Australia. *Plant and soil*. 2011;345(1-2):47-58.

- Sgouridis F, Ullah S. Relative magnitude and controls of in situ N₂ and N₂O fluxes due to denitrification in natural and seminatural terrestrial ecosystems using ¹⁵N tracers. *Environmental Science & Technology*. 2015;49(24):14110-9.
- Shen Y, Zhu L, Cheng H, Yue S, Li S. Effects of biochar application on CO₂ emissions from a cultivated soil under semiarid climate conditions in Northwest China. *Sustainability*. 2017;9(8):1482.
- Singh JS, Seneviratne G. *Agro-Environmental Sustainability, vol. 2. Managing Environmental Pollution*. 2017.
- Smith P, Martino D, Cai Z, Gwary D, Janzen H, Kumar P, McCarl B, Ogle S, O'Mara F, Rice C, Scholes B. Greenhouse gas mitigation in agriculture. *Philosophical transactions of the royal Society B: Biological Sciences*. 2008;363(1492):789-813.
- Sohi S, Lopez-Capel E, Krull E, Bol R. Biochar, climate change and soil: A review to guide future research. *CSIRO Land and Water Science Report*. 2009;5(09):17-31.
- Sohi SP, Krull E, Lopez-Capel E, Bol R. A review of biochar and its use and function in soil. *Advances in agronomy*. 2010 ;105:47-82.
- Stavi I, Lal R. Agroforestry and biochar to offset climate change: a review. *Agronomy for Sustainable Development*. 2013;33:81-96.
- Steiner C, Glaser B, Geraldes Teixeira W, Lehmann J, Blum WE, Zech W. Nitrogen retention and plant uptake on a highly weathered central Amazonian Ferralsol amended with compost and charcoal. *Journal of plant nutrition and soil science*. 2008;171(6):893-9.
- Stewart CE, Zheng J, Botte J, Cotrufo MF. Co-generated fast pyrolysis biochar mitigates greenhouse gas emissions and increases carbon sequestration in temperate soils. *Gcb Bioenergy*. 2013;5(2):153-64.
- Su X, Wang Y, He Q, Hu X, Chen Y. Biochar remediates denitrification process and N₂O emission in pesticide chlorothalonil-polluted soil: role of electron transport chain. *Chemical Engineering Journal*. 2019;370:587-94.
- The Food and Agriculture Organization of the United Nations (FAO). *Agriculture, forestry and other land use emissions by sources and removals by sinks*. Rome: The Food and Agriculture Organization of the United Nations, Statistics Division (ESS); 2014.
- USEPA. Sources of Greenhouse Gas Emissions. Available online: <https://www.epa.gov/ghgemissions/> (accessed on 5 August 2022).
- Van Der Gon HD, Neue HU. Oxidation of methane in the rhizosphere of rice plants. *BiolFertil Soils*. 1996;22(4):359-366.
- Verheijen F, Jeffery S, Bastos AC, Van der Velde M, Diafas I. "Biochar application to soils." A critical scientific review of effects on soil properties, processes, and functions. EUR 24099, 162 2010.

Wang C, Shen J, Liu J, Qin H, Yuan Q, Fan F, Hu Y, Wang J, Wei W, Li Y, Wu J. Microbial mechanisms in the reduction of CH₄ emission from double rice cropping system amended by biochar: a four-year study. *Soil Biology and Biochemistry*. 2019;135:251-63.

Wang J, Akiyama H, Yagi K, Yan X. Controlling variables and emission factors of methane from global rice fields. *Atmospheric Chemistry and Physics*. 2018 ;18(14):10419-31.

Wang K, He C, You S, Liu W, Wang W, Zhang R, Qi H, Ren N. Transformation of organic matters in animal wastes during composting. *Journal of hazardous materials*. 2015;300:745-53.

Wang YQ, Bai R, Di HJ, Mo LY, Han B, Zhang LM, He JZ. Differentiated mechanisms of biochar mitigating straw-induced greenhouse gas emissions in two contrasting paddy soils. *Frontiers in microbiology*. 2018;9:2566.

Wang Z, Li Y, Chang SX, Zhang J, Jiang P, Zhou G, Shen Z. Contrasting effects of bamboo leaf and its biochar on soil CO₂ efflux and labile organic carbon in an intensively managed Chinese chestnut plantation. *Biology and fertility of soils*. 2014;50:1109-19.

Wang Z, Zheng H, Luo Y, Deng X, Herbert S, Xing B. Characterization and influence of biochar on nitrous oxide emission from agricultural soil. *Environ. Poll.* 2013;174:289-96.

Waqas M, Asam Z, Rehan M, Anwar MN, Khattak RA, Ismail IM, Tabatabaei M, Nizami AS. Development of biomass-derived biochar for agronomic and environmental remediation applications. *Biomass Conversion and Biorefinery*. 2020;11:339-61.

Wassmann R, Lantin RS, Neue HU, Buendia LV, Corton TM, Lu Y. Characterization of methane emissions from rice fields in Asia. III. Mitigation options and future research needs. *Nutrient Cycling in Agroecosystems*. 2000;58:23-36.

Weldon S, Rasse DP, Budai A, Tomic O, Dörsch P. The effect of a biochar temperature series on denitrification: which biochar properties matter?. *Soil Biology and Biochemistry*. 2019;135:173-83.

Windeatt JH, Ross AB, Williams PT, Forster PM, Nahil MA, Singh S. Characteristics of biochars from crop residues: potential for carbon sequestration and soil amendment. *Journal of environmental management*. 2014;146:189-97.

Woolf D, Amonette JE, Street-Perrott FA, Lehmann J, Joseph S. Sustainable biochar to mitigate global climate change. *Nature communications*. 2010;1(1):56.

Xiao Y, Yang S, Xu J, Ding J, Sun X, Jiang Z. Effect of biochar amendment on methane emissions from paddy field under water-saving irrigation. *Sustainability*. 2018;10(5):1371.

Xu HJ, Wang XH, Li H, Yao HY, Su JQ, Zhu YG. Biochar impacts soil microbial community composition and nitrogen cycling in an acidic soil planted with rape. *Environmental science & technology*. 2014;48(16):9391-9.

Zhang A, Cui L, Pan G, Li L, Hussain Q, Zhang X, Zheng J, Crowley D. Effect of biochar amendment on yield and methane and nitrous oxide emissions from a rice paddy from Tai Lake plain, China. *Agriculture, ecosystems & environment*. 2010;139(4):469-75.

Zhang A, Liu Y, Pan G, Hussain Q, Li L, Zheng J, Zhang X. Effect of biochar amendment on maize yield and greenhouse gas emissions from a soil organic carbon poor calcareous loamy soil from Central China Plain. *Plant and soil*. 2012;351:263-75.

Zheng J, Doskey PV. Modeling nitrous oxide production and reduction in soil through explicit representation of denitrification enzyme kinetics. *Environmental science & technology*. 2015;49(4):2132-9.

Zhu X, Burger M, Doane TA, Horwath WR. Ammonia oxidation pathways and nitrifier denitrification are significant sources of N₂O and NO under low oxygen availability. *Proceedings of the National Academy of Sciences*. 2013;110(16):6328-33.

Zimmerman AR, Gao B, Ahn MY. Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils. *Soil biology and biochemistry*. 2011;43(6):1169-79.

UNDER PEER REVIEW