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Carbon Negative Biochar Technology for Mitigating Methane Emissions

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Abstract

Higher global warming and irregular climatic patterns significantly impacted ecosystems, mainly due to the increase in greenhouse gases from agriculture. Methane has emerged as a primary contributor among gases, hence the need to curb CH_4 in combating global warming. Among the best mitigative options, the use of biochar, produced by charring crop residues at high temperature in reduced oxygen, emerges. The stable, high-carbon material sequesters soil carbon in addition to minimizing emission of CH_4 and N_2O. When applied to soil, biochar enhances crop productivity, improve resource use efficiency through sustainable conversion of crop residues. Its porous texture stimulates soil microbes, soil health and sustains long term fertility. Due to its permanence, the use of biochar constitutes an effective carbon capture and sequester instrument. When applied in broader sustainable applications, the material contributes significantly to climatic change mitigation in addition to the establishment of long-term resilient crops.

Keywords: Biochar, Fertility, Global warming, Sequestration

Introduction

Increases of greenhouse gases (GHGs), *viz.*, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3) and water vapour were the main cause of increases of the temperature of the globe. These gases have the capability of storing as well as re-emitting the long-wave radiation, which results in increases of the temperature of the surface of the globe intensified greenhouse effect. Among these, carbonaceous gases such as CO_2, CH_4 as well as CHCs are of immense environmental hazard. Methane is of special significance due to its largest global warming potential (GWP), *i.e.*, 12±3 years. Around 30% of the temperature rise of the globe is attributed to agriculture, of which mostly results due to emission of methane. Important contributors include wetlands, cultivation of rice, burning of biomass as well as composting. It is of immense seriousness as well as importance for an ecological hazard that biomass burning is; hence, identifying effective measures for its effective use makes it inevitable for achieving sustainable development. Sequestration of carbon stores atmospheric CO_2, checking climate change. Due to its high carbon content and its special properties of the biochar, producing biomass as biochar under pyrolysis has been an encouraging as well as sustainable method.

Methanogenesis and Methane Emissions from Cropping Systems

Methanogens in the absence of oxygen produce CH_4 as a byproduct, which is known as methanogenesis. They are strictly anaerobic and thrive in oxygen-deprived conditions. Methanogenesis is achieved by obligate archaea that employ soil organic matter for supplying the carbon needs, producing methane as a byproduct. Methanogens are classified as aceticlastic, hydrogenotrophic and methylotrophic based on the substrates that they employ. Rice-based cropping systems and wetlands are major sources of methane emission, as flooded conditions lead to the development of an anoxic environment that favours CH_4 production (Figure 1). During anoxic conditions, methanogens facilitate the reduction of carbonaceous compounds to generate energy through ATP synthesis. Under water-logged conditions, when soil redox potential (Eh) falls below -200 eV, a group of hydrogenotrophic and aceticlastic methanogens

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(*Methanogenic archaea*, *viz.*, *Methanocella*, *Methanosaeta*, *Methanobacterium* and *Methanoregula*) become abundant and proactively produce methane.

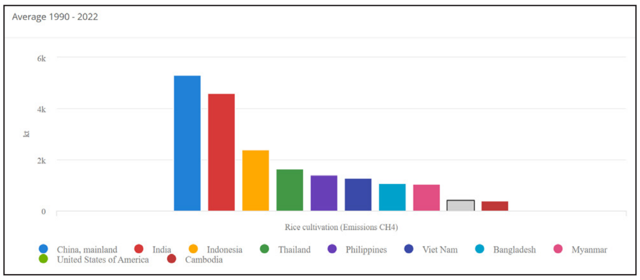

Figure 1: Top countries leading in global methane emissions (FAOSTAT, 2023)

Methanotrophs and Methane Oxidation

Unlike methanogens, methanotrophs are methane consumers that mostly exist under well-oxygenated (oxidized) soil horizons. All around the world, using the methanotrophic bacteria, the atmospheric emission of methane can be reduced by nearly 50% as by evaluating their annual consumption of 70-300 Tg CH_4 (Figure 2). Based on the conditions in which they thrive in, they are classified into two types: Type I and Type II. Type I are generally dominant in aerobic environments with low methane concentration, whereas type II methanotrophs differ from type I in their metabolic pathways and ecological niches and are generally dominant in methane-rich and anaerobic conditions. Methanotrophs utilize the oxygen present in the rhizosphere through the aerenchyma tissues, which oxidize methane into CO_2. Methanotrophs oxidize the methane under aerobic conditions and produce CO_2. The methane oxidation potential of methanotrophs can be enhanced by adopting carbon-negative technologies such as biochar, whose profound impacts can be seen in various agricultural systems.

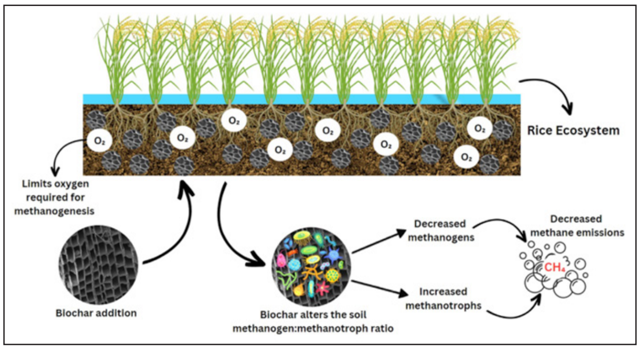

Figure 2: Biochar derived microbial alterations in rice field (adapted from Nandipamu *et al.*, 2024)

Biochar: A Carbon Negative Technology

Biochar is a carbon-negative technology produced through the pyrolysis of agricultural residues and manures at high temperatures. Rich in carbon, it remains stable for a longer period in soils, making it the most recalcitrant form of carbon. Apart from this, biochar plays a major role in carbon sequestration. It exhibits distinctive properties essential for mitigating methane emissions. With its high porous structure, micropore formation, porous and large specific surface area, strong cation/anion exchange capacity, carbon content and more versatile electron transfer, biochar holds potential to address the build-up of methane emissions from agriculture.

Biochar Role in Methanogenesis and Methanotrophy

Biochar is resistant to weathering due to its recalcitrant nature and unique features, particularly the nuanced correlations between the soil matrices and the soil microbiota. It demonstrates potential as a carbon-negative technology. Biochar has high specific surface area and is porous, providing good conditions for the presence of microbial communities, such as methanotrophic bacteria. Methanotrophic bacteria infect the microsites of the biochar, hence promoting the effectiveness of methane oxidation, thereby reducing net emission of methane. The adsorption of methane is promoted by the existing functional groups, such as the hydroxyl, carboxyl as well as aromatic fractions, that are present on the biochar and they also immobilize the methane, thereby reducing its emission into the environment.Biochar makes the copper bioavailable for the methanotrophic bacteria, which is required for the methane oxidation and it also elevates the labile carbon and nitrogen, apart from maintaining optimal pH conditions for their proliferation. By reducing the methanogenic archaea (mcrA) while increasing the methanotrophic bacteria (pmoA) abundances, biochar lowered the mcrA/pmoA ratio, altering the methane emissions.

Role of Biochar in Paddy Fields and Other Cropping Systems

Biochar effectively reduces the methane emissions in various ways, like first it can improve soil aeration and promote the methane oxidation, secondly it alters the methanogenic and methanotrophic biomes and lastly by adsorption of the methane gas with the help of functional groups. Incorporating biochar into paddy fields modifies a wide range of soil physicochemical and microbial properties, particularly by altering the ammonium concentration, which disrupts methanogenesis by constraining the methanogen proliferation. A 10.9% to 22.8% reduction in methane emissions was observed with the incorporation of rice husk biochar in rice-based cropping systems (Singh *et al.*, 2023). Whereas, in other cropping systems where aerobic conditions prevail, the incorporation of biochar makes the soil condition more congenial for the development of the methanotrophic bacteria and methanotrophic archaea, which are involved in the oxidation of methane. Biochar addition significantly increased soil organic carbon stock by 32.6% in the first season and 43.5% in the second season, while reducing cumulative CH_4 emissions by 21.1% and 24.9%, respectively (Sriphirom *et al.*, 2021).

Limitations

Even though the biochar is observed to function to reduce GHG's, its effect largely depends on the nature of the feedstock, temperature of pyrolysis and soil (Fida Banu, 2023). For instance, when the pH of the biochar is extremely high, this can stimulate an increase of volatilization of N within the ammonia, largely if the soil is basic. Quality of the biochar can also determine its effectiveness. Even though the biochar is stable depending on its nature of being recalcitrant, its effectiveness in the long term is still unknown.

Conclusion

Biochar, through its dynamic interactions, can either alter vast biogeochemical cycles or store carbon for extended time frames, thereby decreasing CO_2 emission. It also alters soil microbial assemblages and promotes soil microbiota development that helps in cycling of the carbon cycle as well as reduces methane emission. Its advantages, however, could only be enjoyed when combined into numerous sustainable practices like composting, conservation agriculture and being part of other more holistic climate mitigation measures.

Future Prospects

Research focused on the biochar application across various cropping systems and identifying region-specific recommendations. Apart from the direct use, various biochar-based materials can also be developed, like nutrient-doped or mineral-coated biochars, which increase their capacity to mitigate the GHG emissions and are also effective in nutrient management. Biochar-microbial dynamics should also be explored for effective understanding of the mechanism. To promote the deployment of biochar at the field level, we should involve policymakers and stakeholders and organize comprehensive training for its effective implementation.

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