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Review article

Agronomic and remedial benefits and risks of applying biochar to soil: Current knowledge and future research directions

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ABSTRACT

'Biochar' represents an emerging technology that is increasingly being recognized for its potential role in carbon sequestration, reducing greenhouse gas emissions, waste management, renewable energy, soil improvement, crop productivity enhancement and environmental remediation. Published reviews have so far focused mainly on the above listed agronomic and environmental benefits of applying biochar, yet paid little or no attention to its harmful effects on the ecological system. This review highlights a balanced overview of the advantages and disadvantages of the pyrolysis process of biochar production, end-product quality and the benefits versus drawbacks of biochar on: (a) soil geochemistry and albedo, (b) microflora and fauna, (c) agrochemicals, (d) greenhouse gas efflux, (e) nutrients, (f) crop yield, and (g) contaminants (organic and inorganic). Future research should focus more on the unintended long-term consequences of biochar on biological organisms and their processes in the soil.

Contents

1. Introduction

The carbon-rich by-product produced through thermal degradation of organic materials like agricultural crop residues and wood waste in an oxygen depleted environment (pyrolysis) is termed 'biochar' (Lehmann et al., 2011). Biochar is an emerging technology with the potential to improve countries' food security while potentially

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sequestering carbon (C) to mitigate climate change (Lehmann and Joseph, 2009; Masek et al., 2011). Being used solely for environmental and agronomic purposes and not for fuel, biochar's properties make it distinct from traditional charcoal. Many studies and reviews highlighted the potential benefits of biochar application as soil amendment covering issues such as waste management, production of bioenergy, enhancing soil fertility through alteration in soil pH, improved nutrient retention through cation adsorption, reduction in nitrous oxide (NO) and methane (CH_4), along with CO_2 emissions and sorption of organic contaminants, besides various other productivity benefits (Atkinson et al., 2010; Saranya et al., 2011; Choppala et al., 2012; Jones et al., 2012; Cayuela et al., 2014; Van Zwieten et al., 2014; Jeffery et al., 2015). As a promising soil amendment, biochar is also increasingly attracting the attention of policy-makers in developed countries like the US, Japan, Europe and some developing countries. Though the potential benefits of biochar have been recently confirmed by a number of studies (Atkinson et al., 2010; Beesley et al., 2011; Lehmann et al., 2011; Junna et al., 2014), hazards, risks and other negative implications associated with biochar technology are yet to be fully understood (Kookana et al., 2011; Singh et al., 2015).

One of the unintended consequences has been that biochar changes soil microbial communities and their abundance (Grossman et al., 2010; Liang et al., 2010). Such changes may alter the activity of beneficial soil microbes and nutrient cycles that indirectly affect growth and quality of crops, which eventually brings about changes in the concentrations of greenhouse gas emissions (Bruun et al., 2014), especially major alterations in N fluxes (Warnock et al., 2007). The possible relationship between biochar properties and soil biota and their implications for soil process have not yet been systematically explained elsewhere. Sorption of environmental contaminants by biochar (Mohan et al., 2014) limits the potential of priority organic and inorganic pollutants to microbiota for remediation by reducing their availability (Rhodes et al., 2008); the sorbed organics or inorganics that are not amenable for microbial degradation may in the long-term cause the greatest environmental impact (Beesley et al., 2011). Also, immobilization of beneficial elements like N in the soil matrix may pose a risk to crop productivity. Furthermore, 75% of the soil fertility, remediation or crop production studies that utilize biochar so far have not been successful in most cases without amending fertilizers (N/P/K) (Asai et al., 2009; Scheer et al., 2011). Consequently the long-term effects of biochar application in these sectors are still unknown. Along with fertilizer application, adding biochar will also increase crop production costs, which is not economically encouraging. Furthermore, accelerated increase in non-biodegradable soil organic matter by adding biochar, lack of feedstock availability for pyrolysis process, change in soil albedo (amount of light reflected back from the earth to space), and change in herbicide efficiency and rate of application by its sorption by biochar and unstandardized biochar production technology raise an important question. Specifically, biochar really can be considered a viable ecological tool for attaining global food security and climate change mitigation. Indeed, this issue has to date not been discussed except by Kookana et al. (2011).

While critically presenting the available literature that notes the potential benefits of biochar application, our review aims to: (a) discuss a balanced perspective of the agronomic and environmental impacts: advantages and disadvantages of biochar amendment to soil, (b) highlight related issues that need to be adequately addressed for its application to be scientifically sound and sustainable, and (c) identify immediate research needs and suggest directions for future research.

2. Pyrolysis platform: production systems, scalability, feedstock and product quality

Globally, about 41 million tons of biochar are produced by pyrolysis annually (McHenry, 2009). A thermochemical process (greater than 400 °C) that can transform low-density biomass (1.5 GJ m^{-3}) and other organic materials (for example wood chips, crop residues, manures, municipal wastes) in the complete or near absence of oxygen into renewable energy products such as (a) high-energy-density solid — 'biochar' (23.3 GJ m^{-3}), (b) high-energy-density liquid — 'bio-oil' (22 GJ m^{-3}) and (c) relatively low-energy density gas — 'syngas' (7.8 GJ m^{-3}) is termed as 'pyrolysis' (Laird et al., 2009). In contrast to the traditional earthen brick and steel kilns, modern pyrolysis plants incur high capital costs and are expensive to operate continuously; however, they tend to offer greatest returns in terms of efficiencies and greenhouse gas abatement potential (Pratt and Moran, 2010). Pyrolyzers are scalable to process materials in a few milligrams per hour to many tons per hour. The largest fast pyrolyzers in North America can process about 250 t of biomass per day. Pyrolysis systems employed to process biomass can be categorized into four types: (1) slow pyrolysis, (2) fast pyrolysis, (3) flash pyrolysis, and (4) gasification as detailed in Fig. 1. All four differ in terms of alterations to composition of feedstock, temperature and heating rates that result in the production of different amounts of each product (i.e. biochar, bio-oil and syngas) (Sparkes and Stoutjesdijk, 2011; Singh et al., 2015). Different feeds and reactors are used to prepare biochar by pyrolysis. Commonly used reactors include well-swept fixed-bed, bench-scale fixed-bed, auger, vertical tubular, and fluidized bed types (Mohan et al., 2014). So far efforts to improve the process efficiency and optimization of biochar production by controlling the operating conditions have not been undertaken extensively due to competing priorities from bioenergy production.

Feedstock pyrolyses into biochar have been conducted on pine wood, oak wood, oak bark, corn stover, apple wood, canola straw, compost, dairy manure, olive pomace, sugarcane bagasse, rice husk, orange waste, bamboo, switchgrass, wheat straw and peanut straw (Barrow, 2012; Ducey et al., 2013; Cao et al., 2014; Junna et al., 2014; Mohan et al., 2014). Almost any form of organic material including crop residues, forestry by-products, urban yard wastes, industrial by-products, animal manure and sewage sludge can be processed in a pyrolyzer. However, not all organic wastes are suitable for producing biochar that can be used in agricultural activities. This is because some production conditions and feedstock create biochar that cannot retain nutrients effectively, and are susceptible to microbial decay (Ogbonnaya and Semple, 2013). One of the major drawbacks is the feedstock availability because, to date, the plentiful feed supply for biochar production mostly consists of plant and crop residues which constitute the primary domain of agricultural sector beyond the use of forest woody biomass. Indeed, the nutrient-rich animal manure- and municipal waste-based biochar is limited in its use in agricultural soils due to the high risk of contamination from toxic heavy metals and organic pollutants like PAHs. This is despite its positive environmental effects including reduced nutrient run-off and reduction of greenhouse gas emissions (CH_4, NO) (McHenry, 2009).

However, in a recent study it has been proved that biochar generated from sewage sludge has heavy metal contents below the harmful levels so that they are less bioavailable to plants (Hossain et al., 2011). This study also showed that biochar produced at higher temperature (700 °C) is alkaline which can be used to neutralize the acidic soil, improve its soil fertility and sequester C. On the other hand, biochar produced at lower temperatures (300 °C) might be suitable for alkaline soils to correct the alkalinity problems. As sewage sludge-based biochar indicates a great potential for soil applications, further research is required to investigate the possibility of using these environmental wastes in different locations at its different level of contamination as biochar. As time passes it will be possible to develop the necessary infrastructure and social practices to collect clean sewage for biochar production. In this way it may become a superior economic waste management strategy.

It is noteworthy that maximizing biochar production is always at the expense of bio-oil and syngas production which could affect the economics of production (Jeffery et al., 2015). In particular, production of