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Use of Biochar for Sustainable Agriculture

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Abstract

Biochar is the by-product of pyrolysis of organic biomass in an oxygen-free to the oxygen-limited environment. Biochar application to soil has been considered as a way to sequester carbon. Biochar research has become considerably innovative with important key findings on agronomic benefits, greenhouse gas emissions, soil remediation, soil fertility, soil health, *etc.* This review discusses the potential use of biochar in sustainable agriculture for improving crop yields, soil fertility, and nutrient cycling, along with potential risks involved with biochar application and strategies to avoid these risks. Biochar has the potential to improve crop productivity mainly by increasing nutrient and water use efficiency. However, improvements to crop production are often observed in nutrient-poor soils, while its application to fertile soils does not always improve crop yield. Production of biochar from good quality biomass sources at the proper temperature is a prerequisite for its use as a soil amendment to improve soil health, plant growth and crop production. The long-term effects of biochar on soil functions and its fate in different soil types require more research. Biochar may change the soil biological community composition and abundance, and the retention of pesticides applied. The key findings of biochar research have continually progressed, but more research is required before definitive recommendations can be made to end users regarding the effects of biochar application across a range of soil, climate and land management practices.

Introduction

Sustainable agriculture is the production of food, fibre, or other plant and animal products using farming practices that protect the environment, public health, human communities, animal welfare and economic development (**Fig. 1**). The aim of sustainable agriculture is to meet human's food and social needs without compromising the ability of future generations to meet their own needs. Sustainable agriculture is also the study of relationships between organisms and their environment, an understanding of ecosystem services. Food production has increased significantly in the world, but for meeting the increased demand of the growing population, it has to increase significantly by 2050. Higher crop production often arises from the use of improved crop varieties, fertilizers, pest control and irrigation, which have resulted in meeting food and nutritional demand. Despite high productivity, farmers face various constraints associated with sustainable agricultural systems. The present-day agriculture has challenged to fulfil various objectives of achieving food, fodder, fibre and fuel

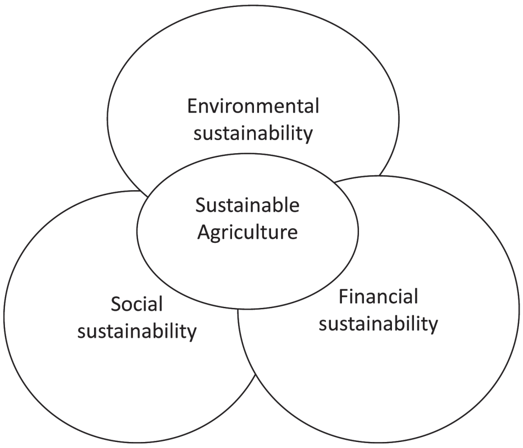

Fig. 1. Sustainable agriculture – interactions among environmental, social and financial sustainability

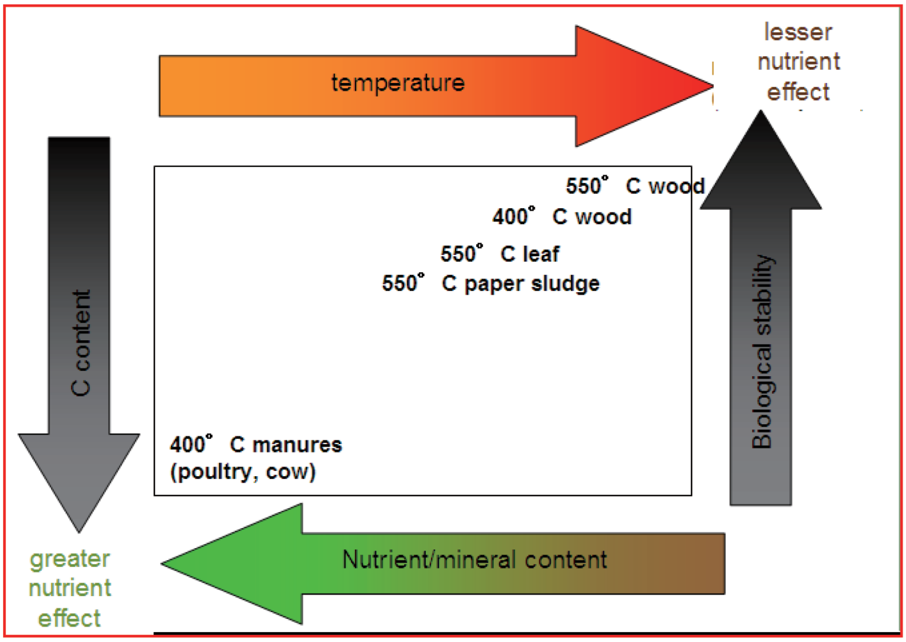

Fig. 2. Effect of temperature on the nutrient availability of plant and derived biochars (Source: Krull ES, CSIRO)

security as well as sustainability with emphasis on restoring soil resources, improving water quality, mitigating climate change and preserving natural resources for long-term use. With the new emphasis on sustainable agriculture comes a reviving of interest in soil health which emphasizes the integration of biological, chemical and physical measures of soil properties that affect farmers profit and the environment. The productive soil is an essential component of a sustainable environment which is the foundation upon which sustainable agriculture is built. For managing soil health certain organic amendments are need to be added. Among these amendments, the potential of biochar as a soil amendment in agriculture is recently recognized through the technology still remains underutilized in the farm level even though researches have progressed a lot in the past several years (Hussain *et al*., 2017).

Recently, research on biochars has focused on enhancing plant growth, soil fertility, carbon sequestration, activities of microorganisms, mitigating climate change and remediation of contaminated soil (Anawar *et al*., 2015; Biederman and Harpole, 2013; Chan *et al*., 2007; Solaiman *et al*., 2010). Because of the rapidly growing interest in biochar, this review articles exploring different aspects of the applications of biochar for crop production, improving soil fertility, microbial activities, C sequestration, greenhouse gas emission and alleviation of soil constraints. Furthermore, characterization of properties and functions of biochars, including improvement in soil biology and fertility, are elucidated.

Biochar characteristics

Biochar is the by-product of thermal combustion, called pyrolysis, of feedstock in the absence of or limited amount of oxygen at low temperatures (300-700°C). Commonly biochar has high carbon (C) content and varying C to nutrient ratio depending on the quality of feedstock used to produce biochar (**Fig. 2**). Commonly used feedstock for biochar production are either plant or animal biomass such as wood chips, crop residues, chicken manures and cow manures, and the suitability of these feedstocks for soil application is reliant on physical, chemical, economic and management factors. In addition, biochar is a highly porous materials and poses a large surface area (Downie *et al*., 2009), and can develop dual surface charges (negative and positive charged) suggesting that biochar has anion and cation exchange capacities, thus decreasing leaching (Lehmann *et al*., 2003), enhancing adsorption (Cheng *et al*., 2008) and increase nutrient retention (Madiba *et al*., 2016). Pyrolysis temperature and feedstock characteristics are largely controlling the physicochemical properties e.g. nutrients composition, particle and pore size distribution of the produced biochar (**Fig. 2**). For example, biochar properties reported having cation exchange capacities (CECs) ranged from 0 to 40 $\text{cmol}_c\ \text{kg}^{-1}$, C/N ratio from 7 to 500 or even higher and pH from neutral to alkaline (Joseph and Lehmann, 2015). Even though such inconsistency makes it challenging to identify the underlying mechanisms behind recognized effects but it also delivers a possibility to produce engineered biochar with required properties for a particular field site depending on soil type, hydrology, land use, soil contaminants and so on.

Effect of biochars on seed germination

Biochars may contain undesirable compounds such as crystalline silica, dioxin, polyaromatic hydrocarbons, phenolic compounds and heavy metals that are harmful to plants, microbes and even humans (Cao *et al*., 2009; Thies and Rillig, 2009) as well as essential nutrients based on feedstocks used for biochar production (Gaskin *et al*., 2008). Some of these compounds in biochar have the potential to either inhibit or stimulate seed germination and seedling growth. Biochar has been reported to both increase (Chan *et al*., 2008; Yamato *et al*., 2006) and decrease (Deenik *et al*., 2010) plant growth and yield but some investigations reported the impact of biochar on early stages of plant growth such as on seed germination and seedling growth (Solaiman *et al*., 2012). Van Zwieten *et al*. (2010) showed that germination of wheat seed was increased with a 10 t/ha of paper mill biochar. In contrast, Free *et al*. (2010) stated that seed germination and early growth of maize were not influenced by biochars produced from a range of organic sources of feedstocks. The application of biochar to soil can alter organic matter mineralization (Steiner *et al*., 2008; Wardle *et al*., 1998) which is linked to the release of nutrients such as nitrogen (Manzoni *et al*., 2008). The resulting change in a nutrient status of the soil may affect both seed germination and seedling growth. Application of biochar to acidic soils can increase soil pH to alkaline levels, especially if higher rates of biochar are applied and changes occur to soil cation exchange capacity (Ogawa, 1994). The variable characteristics of biochar indicate that biochar responses will depend on the type and rate of biochar applied to soil as well as on soil characteristics such as soil C, pH, CEC and so on. As we tested, biochar can increase seed germination and initial root growth at a certain rate of application and then gradually decreases as the biochar rate increases (**Fig. 3**).

Biochar increases soil water holding capacity

The application of biochar at higher rates can increase soil water retention directly due to its high surface area (Lehmann, 2007) and indirectly via subsequent increases in the soil organic C (Blanco-Canqui and Lal, 2004). Several investigations of biochar application on crops reported that biochar may enhance soil water holding capacity (Sohi *et al*., 2009; Solaiman *et al*., 2012). This property of biochar may decrease the effects of drought on crop productivity in drought-prone areas like in Western Australia. Water holding capacity is largely correlated with the physical properties of biochar such as high surface area and high porosity. However, there is some debate because the water holding capacity is related to the type of feedstock that was used to produce the biochar, as well as the pyrolysis conditions of the biochar's production. These factors can influence the surface and pore structure of the biochar. However, if climate change leads to even higher drought conditions in many agricultural production areas of the world, biochar as a soil amendment from various feedstocks may still have a considerable positive impact on retaining soil water even though it is very variable (Lehmann and Joseph, 2009). A careful attention is needed to choose biochar for drought-prone conditions.

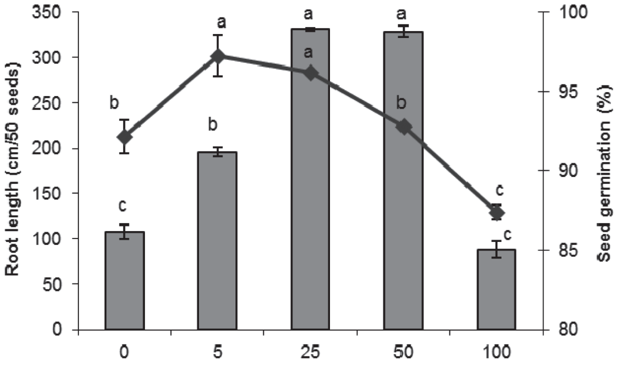

Fig. 3. Root length (histogram) and germination (line graph) of wheat var. Calingiri seeds with different rates of biochar

Role of biochar in soil carbon sequestration and climate change mitigation

The most encouraging aspect of biochar is that it could be an important renewable energy source with the potential to significantly mitigate greenhouse gas (GHG) emissions and slow climate change. The sequestration of biochar in soil, which makes soil darker in colour, is a robust way to store carbon to mitigate CO_2 emission (Lehmann, 2007). An illustration of this capacity of biochar that are estimates of potential atmospheric C offsets proposed by Lehmann, 2007 (showed in **Fig. 4**). The first part of the illustration shows the C sequestration process that represents the natural carbon cycle such as plants pull CO_2 from the atmosphere, part of that carbon is made into the plants' structures through the photosynthesis process. When plants die, they sequester C into the soil, but most of the C is rather quickly released back into the atmosphere as CO_2 through plant respiration and mineralization by soil microbiological activities. The relative amounts of CO_2 are more or less balanced and hence the process is called C neutral (Lehmann, 2007). Carbon neutral means that there is no net C added to the atmosphere other than what naturally occurs. Climate change is caused by net additions of C, called C positive, to the atmosphere. These additions are primarily due to burning C-based fossil fuel at an increasing rate over the past 500 years. Carbon negative refers to the actual net reduction of C in the atmosphere. The natural process is interrupted by capturing part of the biomass before it reaches the soil directly and using part (25% in the example above) for the production of bioenergy and part for the production of biochar (**Fig. 4**). The illustration shows that the biomass that is converted to energy (potentially in the forms of heat, gas or liquid fuels) releases part of the C in the form of CO_2 back into the atmosphere in an assumed C-neutral process. The other part of the biomass is converted into biochar and because of its stability sequesters all but 5% of the carbon (**Fig. 4**) in the soil and hence has the ability to provide a C negative source of energy. However, the capacity of biochar with energy production to offer C-negative renewable fuel is limited to critical points in the process of its production and consumption. Firstly, it is important that biochar added as a soil amendment remains stable and sequestered for a very long time. In climate change scenario, this refers to the issue of stability and in other words, it would be difficult to claim a permanent sequestration of C if the biochar C that was applied as a soil amendment was immediately released back into the atmosphere through possible soil microbiological mineralization processes. However, most research findings to date clearly demonstrate that biochar added to soil releases C back into the atmosphere at a very slow rate that is in excess of several hundred if not thousands of years (Lehmann and Joseph, 2015). It means a permanent sequestration, it is a much slower release compared with the soil C sequestration that occurs when agricultural practices such as conservation tillage are adopted as a means to mitigate climate change. It also offers safer and likely less expensive C sequestration than other methods related to the storage of CO_2 in the underground using C capture and sequestration technologies. Finally, the C-negative potential of biochar is either enhanced or limited

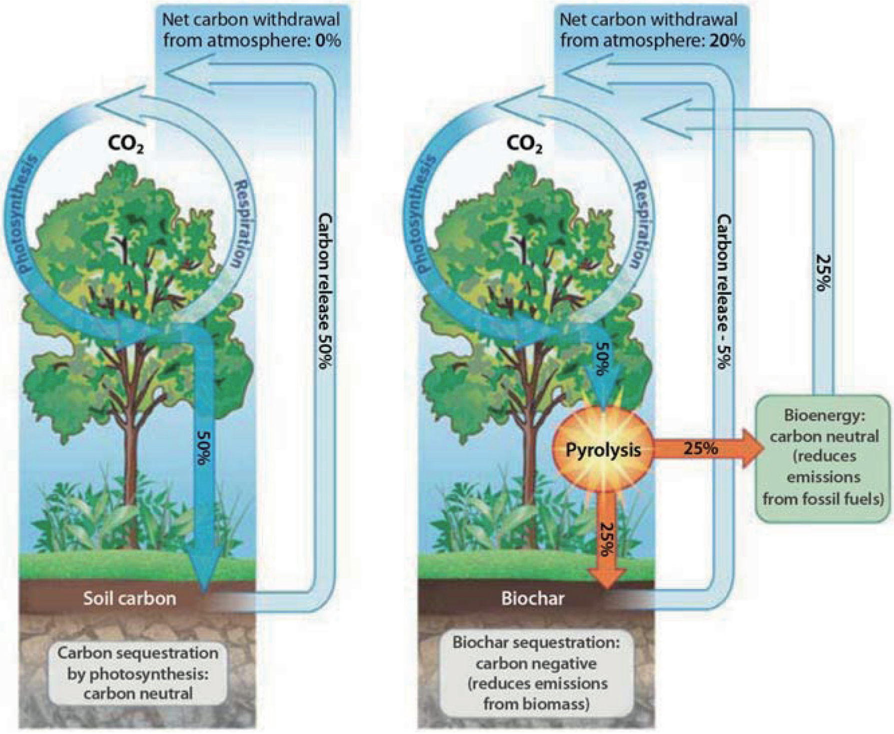

Fig. 4. Biochar can be a carbon-negative renewable fuel source (Lehmann, 2007). Source: International Biochar Initiative. Available at www.biochar-international.org/biochar/carbon and stated by (Schahczenski, 2010)

by the efficiency of energy production and the ability of the overall production process to limit CO_2 and other GHG emissions. In part, this is because of controversy over the research methodologies for measurement of biomass-based energy production (UNEP, 2009). Nonetheless, the life-cycle assessment of biochar needs to be examined for energy efficiency and GHG emissions. Only a few researches have employed this type of analysis, but to date it supports the conclusion that biochar results in a net reduction in GHG emissions (C-negative) and is an efficient use of biomass (Guant and Lehmann, 2008; Lehmann and Joseph, 2009; and Roberts *et al*., 2010).

Effect of biochars on soil health, soil fertility and crop production

Biochars can increase soil C storage and potential C sink, improve soil nutrient retention and nutrient availability, decrease nutrients leaching and maintain the balance of soil ecosystem by adding high aromatic structure into soil humus (Joseph and Lehmann, 2015; Madiba *et al*., 2016). Earlier research suggests that components of C in biochar are highly recalcitrant in soils, for example, the residence time for wood biochar being in the range of 100 to 1,000 years, i.e. around 10-1,000 times longer than residence times of the most soil organic matter (Verheijen *et al*., 2010). However, there is a paucity of data regarding the residence time of all biochars produced from various feedstocks will significantly be varied. Biochar increases the water holding capacity, pH, plant growth and root development as well as rhizobial and mycorrhizal colonization in roots (Solaiman *et al*., 2010; Rondon *et al*., 2007). The current global investigation is addressing the optimal application rates and processes, the effect of biochar additions on soil C sequestration and accumulation of nutrients over the long-term, the interaction of biochar with soil microbial communities and the long-term fate, stability and toxicity in soil needs further investigation.

Biochar is stable and the reactive biochar surface can strongly adsorb toxic substances, such as aluminium, manganese and H^+ in acid soils and arsenic, cadmium etc. in heavy metal contaminated soils (Berek *et al*., 2011). Biochar application into the soil is expected to enhance overall sorption capacity of soils towards anthropogenic organic contaminants e.g. pesticides and herbicides, in a mechanically unlike way than amorphous organic matter. It may greatly remediate toxicity and minimise transport of common pollutants in soils through reducing their bioavailability, increasing their localised accumulation, although the extent and rate of this need to be assessed. Biochar can reduce mobilities of some inorganic and organic pollutants in soil (Beesley *et al*., 2011). Feedstock properties and production temperature of biochar influence capacity of pollutant retention. Highly alkaline and water-soluble C can undesirably mobilise some elements and the large surface area may be toxic to soil fauna but may act as a microbial habitat (Jaafar *et al*., 2014).

Effect of biochars on soil constraints

Soil acidity is one of the major constraints for crop production throughout the world. Biochar can be played an important role in the management of acidic soils. The pH of biochar usually is influenced by the type of feedstock, production temperature and production duration (Liu and Zhang, 2012). For example, at production temperature of

300°C, the biochar produced from corn, peanut, and soybean straws were alkaline, but the pH of biochar produced from straws of canola and wheat were mild acidic (Yuan and Xu, 2011; Yuan *et al*., 2011c). Cheng *et al*. (2006) demonstrated a low pH at 5.4 measured in water when biochar was made at 350°C. The unlike pH values between biochar and soil may be the main cause of soil pH change. Acidic biochar could also increase soil pH when applied in soil with very low pH value (Cheng *et al*., 2006). There are a few studies focusing on the effect of biochar on the pH of alkaline soil. Van Zwieten *et al*. (2010) reported that the application of two biochars with pH values of 9.4 and 8.2 both increased the pH of Ferrosol having initial pH 4.2, but only one biochar increased the pH value of Calcarosol having initial pH 7.7. In mine tailing soil, the pH value of 8.1 was increased to 10.2 when biochar added at 10% application rate (Fellet *et al*., 2011). The research done by Yuan *et al*. (2011a) revealed that the pH value of biochar-amended acidic Ultisols decreased with increasing incubation time, even though the pH was still higher than that of the unamended control. This is because of the production of acidic functional groups from the oxidation of biochar during the incubation process (Cheng *et al*., 2006).

Biochar amendment increased soil pH and exchangeable cations and reduced Al saturation in soils. Association of H^+ ions with biochar and decarboxylation processes was likely to be the main factor neutralizing soil acidity (Wang *et al*., 2014). Therefore, the lack of change in soil pH at the higher biochar rate may be due to the displacement of exchangeable acidity and the high buffering capacity of biochar, thereby, retarding a further liming effect. Biochar type, application rate, and their interaction had significant effects on soil pH, EC, and CEC of the acidic soil of pH < 4.80 (Chintala *et al*., 2014). The addition of biochar in the highly weathered acidic soil recently showed the increase in seed emergence, above ground biomass, vegetation cover, N and P use efficiency and maize growth (Zhu *et al*., 2014). Xu *et al*. (2014) also showed that the effects of biochar application on P sorption were highly influenced by soil acidity. These variations suggest that the increase in P sorption with biochar addition is credited to Ca-induced P sorption and is less affected by Fe and Al oxides. Biochar application is found to have altered soil P availability was dependent on soil acidity, which has important contributions for improving soil productivity. The alkalinity of biochars was a key factor contributing to their liming potential (Yuan *et al*., 2011b) which made soil generally less acidic (Yuan *et al*., 2011c) and the ameliorating effects of biochar on soil pH increased with increasing biochar application rates (Yuan *et al*., 2011a). The increase of crop growth from biochar amendment of a typical Ultisol may result from an increased soil pH and CEC (Peng *et al*., 2011). Liang *et al*. (2014) suggested that biochar application to calcareous soils increased crop yield, soil pH and water holding capacity or could be used in calcareous soils without yield loss or significant impacts on nutrient availability.

Effect of biochars on greenhouse gas emissions from soil

The increase in GHG emission is the key factor of climate change for global warmings and the contribution of CO_2 emission alone is over 70% (IPCC, 2007a). The CO_2 emission through soil respiration is almost 10 times higher than that produced by fossil fuel burning (IPCC, 2007b). Therefore, the decrease of CO_2 emission from agricultural soil to mitigate the climate change is crucial. Biochar use has been suggested to improve soil C sequestration (Lehmann and Joseph, 2009), decrease N_2O emission (Van Zwieten *et al*., 2010; Spokas *et al*., 2009) as well as decrease CH_4 emission (Feng *et al*., 2012). Some studies have focused that biochar can reduce two GHGs responsible for global warmings such as N_2O and CH_4 emissions from the soil, as well as physically store in the soil and have significant impacts for climate change mitigation (Cayuela *et al*., 2014; Felber *et al*., 2014; Verheijen *et al*., 2010). For example, van Zwieten *et al*. (2010) stated that biochar produced from green waste decreased emissions from 1470 to 636 N_2O-N m^{-2} compare to the control (3165 N_2O-N m^{-2}) in a Ferrosol. However, some researcher reported that biochar did not reduce emissions in their experiments (Clough *et al*. 2010; Sheer *et al*. 2011). This displays different biochars affect GHG emissions from soils differently. It is obvious that soil water content (Sanchez-Martin *et al*., 2008), biochar feedstocks either plant or animal origin (van Zwieten *et al.,* 2010; Spokas *et al*., 2009; Yanai *et al*., 2007) and biochar pyrolysis temperature influence the potential to decrease GHG emissions (Singh *et al*., 2010). There are an enormous amount of researches done on the effect of biochar on soil CO_2 emission, however, the outcomes are not conclusive as a result of the diversity of the research materials and methods used.

The mechanisms involved in decreasing GHG emissions by biochar use are complex and speculative. However, basic mechanisms were provided by Yanai *et al*. (2007) who suggest that biochar application to soil increases the activity of microorganisms involved in the reduction of N_2O to gaseous nitrogen (N_2). Moreover, the activity of N_2O-reducing organisms is increased due to the alkalinity of biochar. Similarly, Yuan and Xu (2011) indicated that due to the increase of soil pH by liming effect is believed to decrease emissions and also amending soil acidity. Biochar also has a large surface area which is providing larger adsorption sites for NO_2, NO and N_2O formed and thus decreasing these gases to release from the soil ecosystem (Yanai *et al*., 2007).

Crop residues are either left or burnt in the paddock, returning most of the C to the atmosphere. The burning of these residues in the field releases a large number of pollutants to the atmosphere which causes serious local and regional environmental impacts (Li *et al*., 2007), and converts significant quantities of nutrients to gaseous form, which are then depleted from the site (Haider *et al*., 2013). Over the past several years, the application of biochar has been recommended as a soil amendment in agriculture (Lehmann and Joseph, 2015). Biochar can enhance soil C stock and nitrogen retention as well as improve soil functions (Depmster *et al*., 2012). Crop residues such as rice straw and husk accounted for 2.46 Gt C/yr, which is about 25% of the global CO_2 emissions from fossil fuels (Mattilia *et al*., 2012; Mohammadi *et al*., 2016). Several field trials with biochar application have shown high potential in decreasing GHG emissions and improving crop yield in paddy fields (Dong *et al*., 2013; Liu *et al*., 2014). Sui *et al*. (2016) reported a significant decrease in CH_4 emissions up to 87% following rice straw-derived biochar amendment in Chinese paddy soils. Most of these studies have used high rates (5-48 Mg/ha) straw biochar in rice cropping systems (Liu *et al*., 2014), and Mohammadi *et al*. (2016) considered that the maximum agronomic benefits occur at rates over 18 Mg/ha. However, some research has suggested that biochar can be beneficial at lower rates if treated with minerals (Josheph *et al*., 2015; Blackwell *et al*., 2015). The higher application rates of biochar increase input costs, to overcome this constraint, the development of minerals enriched biochar, having higher surface functionality, exchangeable cations, and higher water-extractable organic compounds have been proposed (Joseph *et al*., 2015; Chia *et al*., 2014). Chia *et al*. (2014) characterized a woody biochar enriched with manures, minerals and clays. Their chemical analyses of the enriched biochar revealed that it has high concentrations of exchangeable cations, available phosphorus and high acid neutralizing capacity. All these amendments were incorporated into the biochar structure and as a result higher concentration of dissolved organic carbon was released into the soil amended with enriched biochar (Lin *et al*., 2012). Joseph *et al*. (2015) observed that an acacia wood-derived biochar mixed with clay, chicken litter, and minerals improved growth of wheat at a low application rate (100 kg/ha). Sarkhot *et al*. (2012) reported that dairy manure effluent enriched woody biochar can promote C and nitrogen storage in soil and mitigate soil GHG emissions.

Life Cycle Assessment has been applied to investigate the carbon footprint of biochar production systems from a perspective of various feedstocks (Clare *et al*., 2014; Mohammadi *et al*., 2016), crop production (Mohammadi *et al*., 2016) or land treated (Peters *et al*., 2015) as a functional unit. These studies are limited to use of raw biochar and did not assess the application of enriched biochar. Further studies need to be carried out using biochar in combination with fertilisers in various farming systems.

Risks associated with biochar use

Several studies have estimated what level of carbon offsets income may be generated from biochar production, but these estimates of life-cycle assessment based on greenhouse gas emissions and price expectations of future unknown carbon prices. One of the important advantages of biochar is that it provides direct soil carbon sequestration compared to other ways of increasing soil carbon sequestration which is not easy to measure. But, the production of biochar has several potential regulatory issues to overcome before a biochar industry can be developed. Major issues include: (i) biochar is very light and easily broken into small particles that can become airborne. Difficult to apply to the soil and can cause potential carbon dust air pollution; (ii) air emission standards from biochar production have not been fully examined and may vary depending on the design of the pyrolysis equipment; (iii) water quality issues related to applied biochar on potentially erodible fields; (iv) potential heavy metal content of biochar and its effect on human and animal health. While these issues are not beyond solution, they will all have to be investigated and will likely add costs to the production and use of biochar as a soil amendment.

Economic potential of biochar for farmers

The economic potential of biochar production for farmers can come from several sources such as (i) a soil amendment that could partially replace fertiliser use; (ii) as a source of heat, bio-oil and gases for farm maintenance; and (iii) as potential income as a carbon credit in a carbon trade market. For example, it is feasible that a farm with significant renewable biomass sources available for harvest could convert biomass to heat and liquid or gas fuel for machinery operation and return the biochar back to the field to enhance fertility and collect a carbon credit payment (see **Fig. 5** for an illustration of possible income sources from biochar production). However, several economic, institutional and regulatory questions need to be answered before such a project could be fully optimized. First, the costs and values of on-farm biochar production need to be considered as well as how much will get back from carbon offsets trade market (Granatstein *et al*., 2009).

Conclusions and recommendations

Biochar potentially influences soil health and functions and interacts with many soil properties because of the wide range of effects from biochar addition to soil. The long-term effects of biochar application on soil health and functions including

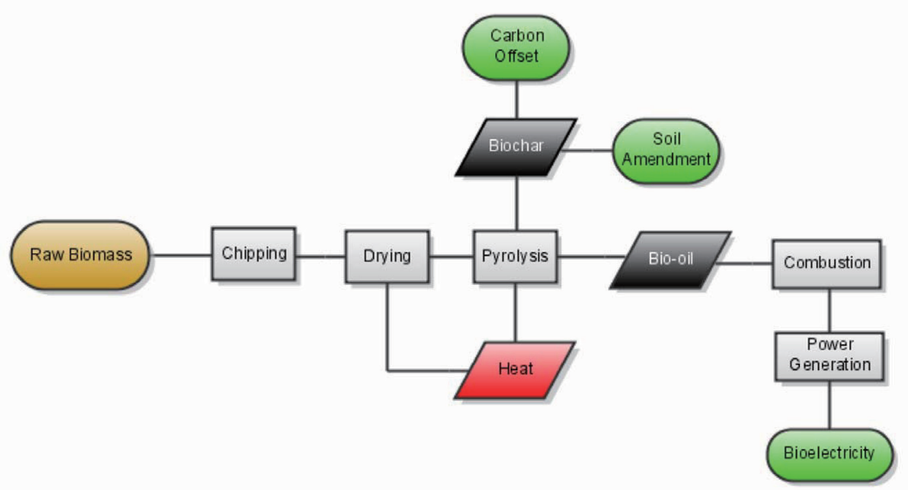

Fig. 5. Potential income sources from biochar production (Figure courtesy of Re-char, www.re-char.com/technology/mobile-pyrolysis) and Schahczenski, 2010).

Table 1. Role of biochar on soil, plant and environmental factors (reproduced from Solaiman and Anawar, 2015).

Statement	Description	Reference
Biochar increased crop production and nutrients uptake	Many studies recorded an increase in crop yield and nutrient uptake but in some cases the negative effects recorded	Blackwell *et al*. 2010 and 2015; Solaiman *et al*. 2010; Chan *et al*., 2007
Biochar increases arbuscular mycorrhizal colonisation in plant roots	Biochar increases soil physicochemical properties; indirect effects on mycorrhizae with interactions with indigenous soil microbes; plant-fungus signalling and detoxification of allelochemicals on biochar; and avoid from fungal grazers	Warnock *et al*., 2007; Solaiman *et al*., 2010
Biochars work as microbial habitats	Biochar increases or decreases soil microbial biomass and microbial activity depending on nutrient availability in soils	Steiner *et al*., 2008;Dempster *et al*., 2012; Jaafar *et al*., 2014
Increases earthworm abundance and activity	Earthworms have been shown to prefer some soils amended with biochar than those soils with no biochar addition	Topoliantz and Ponge, 2005; Van *et al*., 2006
Liming effect	Biochars have neutral to basic pH and several field experiments show an increase in soil pH after biochar application where the initial pH was low.	Cheng *et al*., 2006, 2008
Increases soil CEC	Biochar increases CEC of soil. The efficiency and duration of this CEC increase after addition to soils need to be examined.	Cheng *et al*., 2006, 2008
Effects on N cycle	N_2O emissions depended on the effects of biochar addition on soil hydrology and associated microbial processes. Mechanisms are largely remained to be explored	Yanai *et al*., 2007; Dempster *et al*., 2012
Biochar decreases soil microbial activity and N mineralisation	The activity of the microbial community decreased in the biochar-amended soil, through decreased soil organic matter decomposition and N mineralisation which may have been caused by the decreased microbial biomass carbon	Dempster *et al*., 2012
Biochars influence seed germination and early growth of seedlings	Biochar type and application rate influenced wheat seed germination and seedling growth. Germination and early root growth of mung bean and subterranean clover differed from that of wheat.	Solaiman *et al*., 2012
Biochar influences soil salinity	Biochars absorb salts and mitigate salt stress to plants demonstrating that biochar can ameliorate salt stress effects on plants and suggest uses of biochar to mitigate salinity in agricultural soils	Thomas *et al*., 2013; Lashari *et al*., 2015
Effect of biochars on soil pH dynamics	The pH of biochar is influenced by the type of feedstock, production temperature and production duration. Biochar type, application rate, and their interaction had significant effects on soil pH both in acidic and alkaline soils.	Liu and Zhang, 2012; Chintala *et al*., 2014, Madiba *et al*. 2015
Mobility and loss of biochar in the soil profile	Biochar mobility and loss through the soil profile and into the water resources have been rarely quantified and transport mechanisms remain poorly understood	Sohi *et al*., 2009
Biochar loss with soil by erosion	Spreading biochar to soil is likely to increase erosion of the biochar particles with soil both by wind and water	Jones *et al*., 2008
Effect biochar on soil organic matter dynamics	Effect biochar on soil organic matter dynamicsis influenced by combinations of soil-climate-management factors remains largely unknown	Marschner *et al*., 2008
Soil water holding capacity	Adding biochar to soil can have direct and indirect effects on soil water retention	Sohi *et al*., 2009; Solaiman *et al*. 2012
Priming effect	There is a possible priming effect exists and covers only the short term and a very small number of sample of biochar and soil types	Kuzyakov *et al*., 2000
Role of biochar pore size and connectivity	Although pore size distribution in biochar may alter key soil physical properties and processes (e.g. water retention, aeration, habitat)	Cheng *et al*., 2006
Biochar influences hydrophobicity	Influence of biochars on soil water repellency and hydrophobicity remains largely untested	Doerr *et al*., 2000
Agricultural management practices enhanced decomposition of biochar	Ploughing, sowing, planting, etc. with biochar-amendment influence the breakdown of biochar in the soil, thereby potentially reducing its carbon storage potential	Lehmann *et al*., 2003
Crop residue removal from the paddock for biochar production	Removal of crop residues from paddocks for use as a feedstock for biochar production impose multiple negative effects on soils	Lal and Pimentel, 2007
Biochar increases the sorption capacity of soils towards trace contaminants	Biochar increases the sorption capacity of soils to PAHs, pesticides and herbicides, and therefore influence toxicity, transport and fate of such contaminants	Yang and Sheng, 2003; Sheng *et al*., 2005; Hiller *et al*., 2007
Risk of contamination	Contaminants (e.g. PAHs, heavy metals, dioxins) that may be present in biochar having detrimental effects on soil properties, microbes and their functions.	Collison *et al*., 2009
Distribution and availability of contaminants within biochar	Very little experimental evidence is available on the short- and long-term occurrence and bioavailability of contaminants in biochar and biochar-amended soil.	Brown *et al*., 2009; McHenry, 2009
Reduces greenhouse gas emissions	Biochars decreases N_2O and methane emission from agricultural farming systems; Biochar can be locked in soils as C storage	van Zwieten *et al*., 2010; Feng *et al*., 2012
Occupational health and safety hazards	Dust exposure and fire hazards associated with the production, transport, application and storage of biochar need to be considered and occupational health and safety measures need to be taken to reduce such risks	Blackwell *et al*., 2009

its fate in different soil types and under diverse management practices still need to be explored. The characterization of biochar produced from a range of feedstocks is also vital. The insecurity of crop production gains at the accurate application rate of biochar and lack of information about additional benefits and few other concerns may have resulted in poor uptake of biochar technology in elsewhere in the world. Therefore, Singh *et al*. (2014) suggested exploring new opportunities to value-add to biochar beyond C sequestration by identifying emerging and novel applications of biochar. For example, Joseph *et al*. (2015) reported feeding cows with biochar has potential benefit to soil health and farm production.

Recent discoveries suggest that a proper selection of the feedstock materials and pyrolysis conditions might substantially reduce the emission levels of atmospheric pollutants and particulate matter associated with the biochar production. The implications of pollutants from pyrolysis to human health remain mostly an occupational risk, but a vigorous qualitative and quantitative assessment of such emissions from pyrolysis of biomass feedstock are lacking. While there is potential for reducing GHG emission by biochar addition to soil but careful selection of biochar type and rate of application in a range of soils is essential. In respect to a climate change mitigation perspective, biochar needs to be considered in parallel with other mitigation strategies as it may not be enough as an alternative to reducing GHG emission.

State-of-the-art biochar use strategies can help mitigate GHG emission, while farmers get benefits of improved soils and crop production. However, a risk assessment is necessary to protect the food web and human health. At present biochar research is often fragmented and repetitive. Therefore, national collaborative approaches are needed that will focus on (i) biochar production and characterization, (ii) potential for soil fertility improvement and crop production, (iii) economic analysis that includes life cycle assessment and (iv) environmental impact assessment. This approach should be used overcoming diverse soil issues in sustainable agriculture practices and recommendations for further research relating to biochar application to soil.

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