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Review

Exploring the potential roles of biochars on land degradation mitigation

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Abstract: Land degradation was exacerbated and its management was challenged by population growth and global climate change. The impacts of land degradation on food security, ecosystem services and biodiversity become a more serious problem particularly in developing countries. Biochar, based on the current research findings, is capable to amend degraded lands. This paper reviewed relevant biocharproperties and identified the opportunities of its using for recovering deteriorated lands.Biochar was traditionally recognized as a good absorbent, energy source, and its ash was used by farmers to recover soil fertility. Recent findings revealed that application of biochar improved soil water retention, enhanced soil aggregation, decreased soil bulk density and increased soil infiltration. It also increased soil cation exchange capacity, soil pH, mineral nutrients, reduced nutrient leaching, support microbial population and activities, and suppressed the pest. The sorption capacity of biochar to soil and water pollutants such as Pb, Cu, Ni, Cr, Cd,dioxine, atrazine, and concurrently eliminatedthe environmental problems such as hypoxia, eutrophication, and algae bloom, have also been investigated. Investigation on its role to mitigate climate change revealed that biochar is capable in reducing greenhouse gasesemissions such as CO_2, N_2O, and CH_4. All those beneficial effects of biochars were attributed to its high porosity, large surface area and surface charge, high carbon, ash and nutrient content, and its stability to be degraded. Thus, biochar could be potential for ameliorating degraded lands.

***Key words**: biochar, degraded land, amelioration*

Introduction

Land degradation has been a major global issue during the 20th century and will remain asan important global issue and the international agenda in the future due to its detrimental impact on agronomic productivity, the environment quality, and its effect on food security and the quality of life (Eswaran et al. 2001). Population growth, urbanization sprawl, food security, water shortage, high food price, biofuel, land use change, climate changes, pollution, and magnify of some old challenges such as salinization, desertification, overgrazing, biodiversity loss, erosion, have been identified as the new actual challenges in the current management strategies of land degradation mitigation.

World population projected to reach 9.1 billion, 34% higher than today at 2050 with the high rate growth is in developing countries such as Africa and Asia (Cohen, 2002; Bruinsma, 2011). Consequently, global demand for food, feed and fiber is expected to grow by 70 percent, including nearly 1 billion tonnes of cereals and 200 million tons of meat. To produce the increasing food demand, a considerable land area should be reserves, while the rest arable land areas is limited, at high risk for conversion, have unchangeable ecological functions, and have limited access. Taking these limitations into account, FAO projects that by 2050 the area of arable land will be expanded by 70 million hectares, or about 5 percent. This would be the net balance of an expansion by 120 million hectares in the developing countries and a contraction of arable land in favour of other uses in developed countries by 50 million hectares.

Land use change as a results of continuing expanded global croplands, pastures, plantations, and urban area in recent decades, potentially undermine the capacity of ecosystems to sustain food production, maintain freshwater and forest resources, regulate climate and air quality, and ameliorateinfectious diseases (Foley et al. 2005).

Fischer (2011) predited that climate change and biofuel will contribute to the land productivity and land competition related to provide food for people in 2050.

Consequently, the more efforts and new management strategies should be prepared and addressed to overcome the new challenges of land degradation management in the future.

Biochar, a type of charcoal produced by thermochemical conversion of biomass or biowaste at limited oxigen supply, based on the current research findings, has an ability of restoringdegraded lands. The capability of biochar to restore deteriorated land is evaluated based on the fact that the *terra preta do Indio* or the Amazonian Dark Earth (ADE), an anthropogenic (anthrosol) soil is highlyfertile compared to its adjacent unfertile Ferrasols (Lehmann and Joseph, 2009). ADE soil is not only fertile, but also contains a high black carbon (pyrogenic carbon) with the life cycle of more than thousand years. Intensive investigation during the last decade revealed that biochar can improve soil properties, water quality, absorb chemical pollutants, requester carbon, reduce greenhouse gases emission, reduce water and wind erosions, support microbial growths and activities, and control pests.

The objective of this literature searching study is to review relevant biochar properties and functions, and to exploring itspotential for amending degraded lands. The findings of this study would be used to promote biochar as a sustainable amendment for land degradation mitigation in the future.

Methods

To identify the challenges of land degradation management strategies and biochar roles in restoring degraded land, a substantial amount of articles from journal with a high impact factor, paper from proceedings, report and books was reviewed. Biochars and its potential roles on ameliorating degraded lands in this study were collected from different level of previous studies, but most of them were conducted at laboratory and greenhouse levels using biochars produced from a highly controlled production conditions. The new challenges in managing deteriorated land was identified based on the criteria that it should be a new agent/factor and/or an amplified from the identified agents/factors that are significantly reduced the quality of soil, water, habitats, and species extinction. The potential of biochars to mitigate degraded lands was evaluated based on the criteria that it has a beneficial multiplier effects on soil, water and biodiversity, and it has no or a tolerable negative impact on the ecosystems as a whole or its components. It can be a totally or partially substitute, a complementary, enhancing, or a new added to the conventional land degradation management strategies.

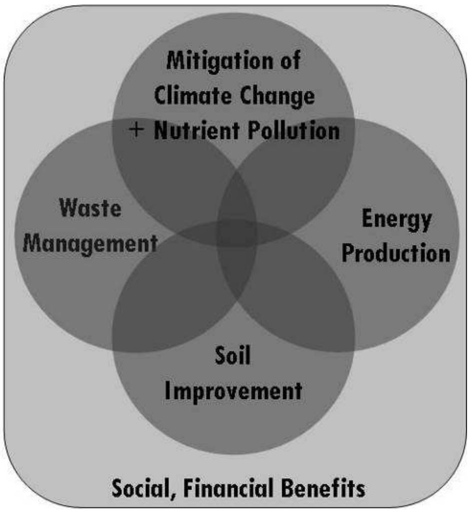
Biochar properties will be reviewed first followed by its amending capacities and the possible management strategies to recover degraded lands.

Biocharsystem

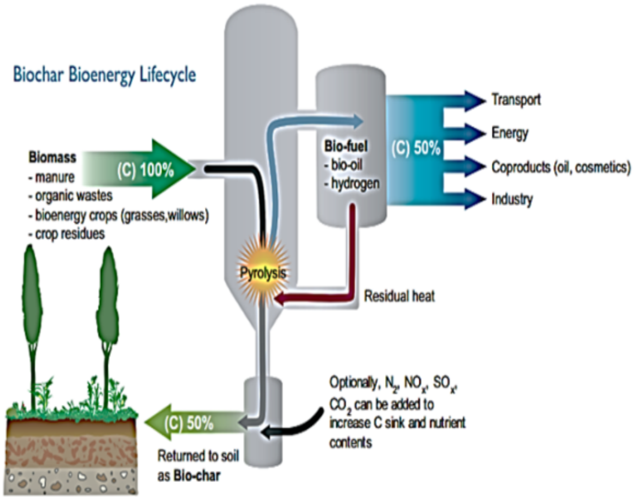
Biochar or pyrogenic carbon as a system has at least four important roles for human life and the environment (Fig. 1A). Improve soil properties and fertility is the first roles, followed by its essential in carbon sequestration and mitigation climate change, supply of bio-energy as an alternative solution for fossil fuel energy crisis, and at the same time provided a new approach for the waste management strategy (Lehmann, 2007; Lehmann and Joseph, 2009).

Pyrolysis process of feedstock produce biochar, syngasand energy (Fig. 1B). Syngas/bio-oil can be utilized as biofuel, the promoting solution for fossil fuel energy crisis, and the solid product (biochar) will be returned to the soil for improving soil productivity and enhancing plant growth, another promoting solution for reducing chemical fertilizer. Incorporation biochar containing high organic carbon will store and sequester carbon under the ground, then reduce CO_2, and nitrous oxide and methane emissionsanother win solution for climate change mitigation. In addition, biochar system utilizes waste as the raw material (recycling wastes) and produce biochar that concurantly adsorbs pollutants and contaminants from soil and water, the other win solution for modern environmental problem. In short, biochar system is the new solution for food security, energy crisis, climate change and environmental problems.

At the community level, heat produced from pyrolysis can be used directly for cooking. Stoves or kilns were designed and used by communities to produce biochar wile cooking. Application of this small scale system will reduce significantly the using of woodfire materials, promote low cost agriculture input by recycling agricultural waste (reduce chemical input and minimize soil and water pollutions), maintain soil productivity, and produce more healthy food.



Source: Lehmann and Joseph, 2009



Source: Lehmann, 2007

Figure1. Biochar system

Biochar properties

Biochar is the carbon-rich product obtained when biomass, such as wood, manure or leaves, is heated in a closed container with little or no available air. In more technical terms, biochar is produced by so-called thermal decomposition of organic materials under limited supply of oxygen, and a relative low of temperature (< 700^{o}C), a process mirror the ancient production of charcoal (Lehmann and Joseph, 2009).

The properties of biochar are determined by its feedstock and pyrolysis temperature and conditions. Different feedstocks and pyrolysis temperatures in particular will produce biochars with different properties. Consequently, biochar has physical and chemical properties that are determine its functions and uses. Some important properties of biochar are surface area (SA) and total porosity (TP), density, mechanical strength, elemental or nutrient content, surface charge (pH, CEC), and some related biological properties related to be habitat of and substrat for microorganisms.Discussion on biochar properties will focus only on surface area and porosity, surface charge and biochars stability, and someother highly relevant properties of biochar for land degradation management.

Surface area and porosity

Surface area is is affected by pyrolysis temperature and biocharfeedstocks. At the lower heat treatment temperature (450^{o}C) the biochar surface area is less than 10 m^2/g and increased to 400 m^2/g at 600-750^{o}C.

Porosity of biochar is resulted from the thermal decomposition of organic materials. With the high temperature micropores tend to widen because it destroys the walls between adjacent pores resulting in the enlargement of pores (Liu and Zhang, 2009). The relationship between surface area and porosity of biochar is presented in Table 1.

Surface area and porosity together determine biochar's water retention, surface chemistry or reactivity, absorption capacity, and some related biological properties.

Table 1. Surface area and volume of different size of biochar's pores

Description	Surface area (m^2/g)	Volume pore (cm^3/g)
Micropores	750-1360	0.2-0.5
Macropores	51-138	0.6-1.0

Source: Laine et al. (1991)

Stability

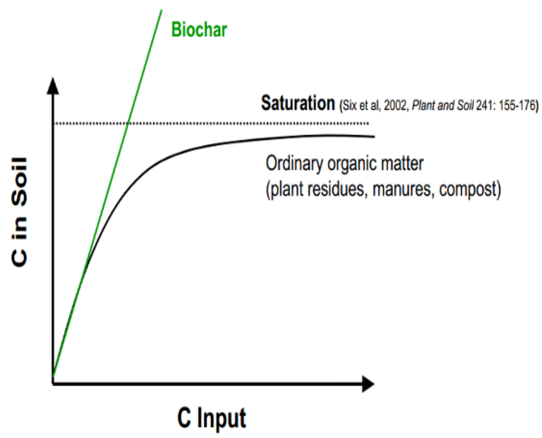
Stability of biochar is the resistance of biochar from biochemical degradation. It is an essential property of biochar because it determines how long biochar as a black carbon is sequestered when applied in soil or environment, and how long it provides benefits to soil and environment (Lehmann et al. 2006).

Biochar contains more than 80% organic carbon of aromatic compound which is very stable in soil or other environments. Comparing to the convential carbon seqestration, biochar system is more efficiently sequester carbon. The efficiency of bicohar is derived from its stability in the soil that accounted for hundred to thousand years campared to organic matter (humus) that have only decade years for its resident time (Figure 3).

The longevity of biochar in the terra preta soils of Amazon region had been radiocarbon dated and found to original from 500 up to 7000 years BP (Neves et al. 2003).

Surface charge

Charge, either negative or positive is developed is derived from the functional groups attached to the main aromatic compunds of biochar. This charge will contribute to the cation or anion exchange capacity of biochar.



Source: Six et al., 2002

Figure 3. Stability biochar and organic matter

pH

The pH of biochar is increased with the increasing of pyrolysis temperature. The accumulation of $CaCO_3$ and basic cations at the higher pyrolysis temperature could be explained this phenomenon that most of the biochars pH is almost higher than 8.

Nutrient content

Nutrient content in biochar can contribute to the nutrient cycle in the soil and environment. Data presented in table 2. shown the nutrient content of some biochars (charcoal) compared to the nutrient content of the Hawaiian acid soil.

Redox potential

Water extract of greenhause waste, eucalyptus wood chip and olive pomace residue have a low redox potential than water, then solubilized Mn and Fe in soil. It means that biochars may participate inchemical and biological redox-mediated reactionsin the soil. Then, biochar could benefited microbial electron shuttling, nutrient cycling, free radical removing, pollutant degradation, contaminant mobilization, and abiotic formation ofhumic structures in soils.

Microbial habitat and substrat

Biochars pores play an important role as a protective habitat and at the same time microbes can ultilize biochar as a source of carbon and other nutrients. Thus, it can support microbial population dan activities in soil and environment (Kolb et al. 2007).

Beneficial effects of biochars on soil and environment

Biochar effect on soil physical properties

Incorporated biocharinto soil altered the soil physical properties such as structure, pore size distribution and density, with implications for soil aeration, water holding capacity and soil workability (Downie et al. 2009; Novak et al. 2012). Evidence suggests that biochar application into soil may increase the overall net soil surface area (Chan et al. 2007) and consequently, may improve soil water and nutrient retention (Downie et al. 2009) and soil aeration and infiltration particularly in fine-textured soils (Kolb et al. 2007). Overall change of soil properties particularly soil water retention and aggregation should be decreased soil erosion (Piccolo et al. 1996; Mbagwu and Piccolo, 1997; Piccolo and Mbagwu, 1990).

One of the good examples is the arid regions of Washington and Idaho, with rainfall totals are very low that creates periods of drought resulting in crop moisture stress. In contrast, annual rainfall in the temperate Coastal Plain region of South Carolina is much larger (1,321 mm) and is generally sufficient for crop water requirements. Despite ample rainfall totals, soil-water deficits still occur in the Coastal Plain region because of poorly distributed rainfall patterns combined with low soil-water storage capacities. Application of switch grass and hardwood biochars into the Norfolk loamy sand soils at these regions improved water holding capacity and water retention at the rate of 1.5 cm of water per 15-cm soil depth (Novak et al.2012). Novak et al. (2009) at the coastal plain of South Caroline region applied of biochar on the Norfolk acidic loamy sand soil was also increased soil pH, phosphorus and sodium (Table 2).

Biochar effect on soil chemicaland biological properties

Biocharis potential to increase soil CEC, pH, and plant nutrients (Lehmann et al. 2003, Liang, 2006; Tryon, 1948; Mbagwu and Piccolo, 1997). Tryon (1948) found increasing amounts of exchangeable bases in sandy and loamy soils after adding 45% hardwood and conifer charcoals. Freshly produced biochar is reported to have an anion exchange capacity (AEC). Biochar exhibits an anion exchange capacity at pH 3.5 which decreased with aging process (Cheng et al.2008). The ability of biochar to retain nutrients should be have a significant contribution of nutrient cycle and particularly nutrient leaching which is have a detrimental effect on hypoxia, algae bloom and eutrophication.

Table 2. Effect of biochar on soil pH, P and Na

Norfolk Soil + Biochar Type	Pyrolysis Temp. (^oC)	Median Values for Soil Characteristics		
		pH[b]	P	Na
		…………kg/ha…………		
Control (0% biochar)	-	5.9a	64a	8a
Peanut hull	400	7.7b	104b	20b
	500	7.7b	85c	10a
Poultry litter	350	8.0c	1280e	791c
	700	9.7d	1812f	1159d
Switchgrass	250	5.9a	74ad	9a
	500	7.0c	94g	9a

[a] Soil incubated with and without biochar for 1-2 h and then air-dried over 2 d for nutrient extraction using Mehlich 1 reagent (dilute HCl + H_2SO_4); [b] Median values followed by a different letter are significantly different using a Student-Newman-Keuls multiple comparasion test at $P = 0.05$. Source: Novak et al. (2009).

Growing investigations on biochars indicated that biochars ameliorate several constraints of acid soils such as increase pH, reduce Al toxicity (Tryon 1948; Nguyen and Lehman 2009; Novak et al.2009; Sing et al. 2010; Deenik et al. 2011; Yuan and Xu, 2011). The capacity of biochar to increase soil pH and to reduce exchangeable Al depends on its ash content and volatile matter content, which is affected by biochar's raw materials as well as its production's processes (Deenik et al. 2011). Soluble salt dissolution, such as potassium and sodium carbonates and oxides, can cause an increase of pH in the water-film around biochar particles (Joseph et al.2010). However, the liming potential should not be only related to ash content, but also to the high surface area and the surface functionality groups of biochar.

Hue (2011) reported that soil-solution Al was significantly complexed by crop residues applied to acid soils. Research findings on black carbon or biochar indicated that unique characteristics of surface chemistry and high reactivity of biochar is partly attributed to the presence of relative functional groups such as phenolic and carboxylic acids (Boehmn, 1994; Cheng et al.2008; Keiluweit et al. 2010). Biocharfeedstocks and pyrolysis conditions largely determine the resulting carbonate concentrations, with the concentrations of carbonates can vary from 0.5 to 33% (Chan et al. 2007) depending on starting conditions. Increasing soil pH of acid soils and addition of nutrients will be created a suitable microenvironment that promotes microbial colonization and activity in catalyzing nutrient transformation for plant growth (Winsley, 2007). All these findings should be established biochar as a sustainable and low cost amendment for acid soils.

Biochar effects on plant growth and production

Improving soil properties and water supply contributed to the plant yields. Maize yield and nutrient uptake were significantly improved with increasing the biochar mixing rate on arid sandy soil. Application of biochar at 15 and 20 t/ha mixing rates was significantly increased maize grain by 150 and 98% as compared with the control, respectively. Maize net water use efficiency (WUE) increased by 6, 139 and 91% as compared with the control, with the 10, 15 and 20 t/ha mixing rate, respectively (Uzoma et al. 2011). Increasing of soybean biomass by 51% with additions of 0.5 t/ha biochar was reported by Iswaran et al. (1980). Tea tree height and volum increased 40% and 20% respectively with addition of biochar (Hoshi,2001). Seven native woody plants' seed germination, shoot height, and biomass production were enhanced 30%, 24% and 13% respectively as resulted from biochar additions. Those example findings revealed that biochar should be considered as a soil ameliorant for increasing food production to feed the growing world population.

Biochar as adsorbent

Biochar or charcoal had been used for a long time to clean water and as an adsorbent. Resent research findings shown that biochar can be used to reduce pesticide and heavy metal pollutant from the soil or solutions. Application of biochar reduced the loss of pesticides due from the soil. Over 35 d, 86–88% of the pesticides were lost from the control soil, whereas it was only 51% of carbofuran and 44% of chlorpyrifos from the soil amended with 1.0% biochar. Despite greater persistence of the pesticide residues in biochar-amended soils, the plant uptake of pesticides decreased markedly with increasing biochar content of the soil. With 1% of biochar soil amendment, the total plant residues for chlorpyrifos and carbofuran decreased to 10% and 25% of that in the control treatment, respectively (Yu et al.2009). The soils amended with 5% biochar produced at 450^{o}C and 1% biochar produced at 850^{o}C had nearly the same sorption capacity for pyrimethanil; however, their desorption processes were very diferent with 13.65% and 1.49% of the sorbed pesticide being released, respectively.

This study suggested that biochar in soil could be an important factor for immobilization of a pesticide and thus affecting its environment fate in soil (Yu et al. 2009). Pinewood and rice husk biochars contained a large amount of oxygen-containing groups on the surface, which were quite effective for lead removal with capacities of 4.25 and 2.40 mg/g for pinewood and rice husk, respectively. The adsorption equilibrium was achieved around 5 h (Liu and Zhang, 2009). Laboratory adsorption experiments were conducted to assess the phosphate removal ability of the two biochars, an activated carbon (AC), and three Fe-modified biochar/AC adsorbents.

The DSTC showed the highest phosphate removal ability with a removal rate around 73%. Our results suggest that anaerobically digested sugar beet tailings can be used as feedstock materials to produce high quality biochars, which could be used as adsorbents to reclaim phosphate (Yao et al.2011). Cr(VI) removal increased with an increase in temperature (Oak wood): 25^{o}C = 3.03 mg/g; 35^{o}C = 4.08 mg/g; 45^{o}C = 4.93 mg/g and (Oakbark): 25^{o}C = 4.62 mg/g; 35^{o}C = 7.43 mg/g; 45^{o}C = 7.51 mg/g). More chromium was removed with oak bark than oak wood (Mohan et al. 2011). Wheat straw biochar produced at 500^{o}C pyrolysis temperature has a capacity to adsorbed Cu^{2+} with the maximum adsorption capacity 11.19 $mg \cdot g^{-1}$ at 30℃. Those findings indicated that biochar with its high adsorption has an important role in mitigation of soil and water pollutants.

Biochar mitigate climate change

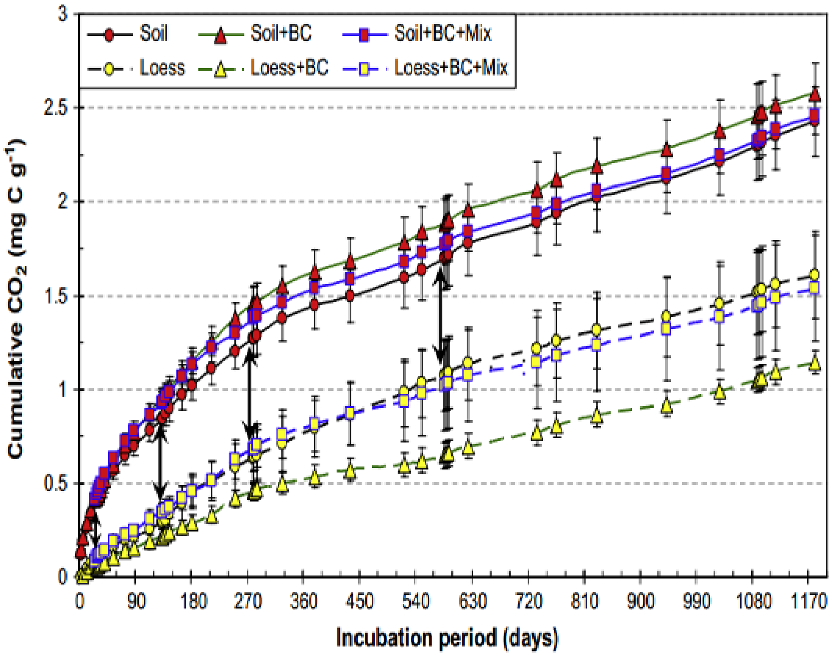
Biochar system was developed to sequester carbon and mitigate climate change, by reducing greenhouse gasses emission. Biochar as a pyrolysis product is very stable or resistant to decay. Mean resident time (MRT) of shoot litter *L. perenne*biochar incubated in soil and loess is 2000 years and a half-life is 1400 years, and the rate of decomposition is very low (Kuzyakov et al.2009). Liang et al. (2008) showed the same low rate of black carbon mineralization after incubated Anthrosol-rich BC and adjacent soils for 532 days (Fig.9).

Biochar has been proved eliminates the nitrous oxide emission and nitrogen leaching. All biochar treatments consistently decreased N_2O emissions, cumulatively by 14 to 73% from the Alfisol and by 23 to 52% from the Vertisol, relative to their controls. The leaching of ammonium was reduced by 55 to 93% from Alfisol and Vertisol, and by 87 to 94% from Vertisol. Increasing effectiveness of biochars in reducing N_2O emissions and ammonium leaching over time was due to increased sorption capacity of biocharsthrough oxidative reactions on the biochar surfaces with ageing (Sing et al. 2009).

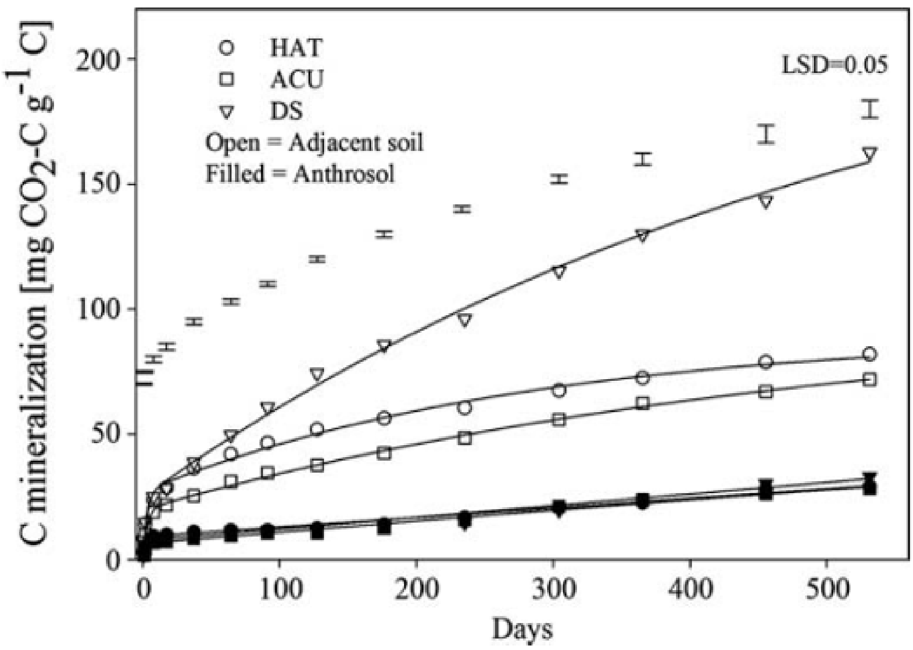
The stability of biochar as carbon black, potential migitation of greenhouse gas emission and efficiency energy produced biochar establishe biochar as a mitigation agent for climate change.

Econoic value of biochar

Life cycle assessment was applied to analysis economic value of biochars by taking into account four coproducts in bichar system: carbon sequestration, renewable energy generation, biochar as a soil amendment, and biomass waste management. The net energy of generated is 4899 MJ/t dry feedstock, net greenhouse gas emissions are negative (-864 to -885 kg CO_2 equivalent), with the carbon emission reduction contributed 62-66%. Application of biochar as a soil amendment may profitable under some conditions if the biochar market price is low enough and/or a carbon offset market exists (Galinato et al. 2011).



Source: Kuzyakov et al. 2008



Source: Liang et al. 2008

Figure 4. Biochar mineralization

Biochar limitation

The limitation of biochar application is concerning with the limited findings and trial of biochar at all levels. Chemical analysis shown that some biochars contain contaminants and will be leached into soil and environment once added as an amendment. Biochar may contain pollutants such as heavy metals and organic compounds, but these are commonly associated with sewage sludge, or treated wood feedstocks, and some contaminants such as polycyclic aromatic hydrocarbons that can be formed during pyrolysis. Verheijen et al. (2010) summarized some potential detrimental effects of biochar including dust from top dressing application, pollutant such as PAHs, heavy metals and dioxins, and negative effects of high rate application.

Conclusion

Land degradation exacerbated by population growth, climate change, land use change, deforestation, overgrazing and over exploitation, and other new detrimental factors that challenging its management strategies. Food production and supply energy for 9.1 billion people by 2050 under climate change pressure while keeping the high environmental quality and protecting biodiversity loss is the serious challenge for managing land degradation.

Biochar system was designed to generate renewable and cheaper energy, amending soil and improving its productivity, managing waste and mitigating the climate change. Implementing and scaling up the biochar system should be significantly contribute to the land degradation management strategies.

Ongoing research findings had established several beneficial effects of biochar application including improving soil properties and soil fertility, increasing plant production, adsorbing pesticides and other chemical pollutants, sequestering carbon and reducing greenhouse gasses emission, utilizing wastes and fast growing invasive species as biochar feedstock, and other advantages such as pest control that are not described in this study.

Thus, biochar system and its products should be considered as an essential component or agent, among others, for the future strategy of land degradation mitigation.

Future direction

Biochar is new developing system that requires further investigations. Evaluation to improve its systems and increasing the beneficial effects of its products should be continued in the future before scaling up to the community level. Research should be addressed to answer some questions such as how to control the biochar quality including the toxic substances containing by biochar? What is the rate of application of each biochar at different soil conditions? How far biochar substituted lime functions in ameliorating acid soils? How to produce stove or kiln to produce biochar efficiently at community level?

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