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Review Article

The Potential of Biochar as an Acid Soil Amendment to Support Indonesian Food and Energy Security - A Review

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ABSTRACT

The future of Indonesian food and energy security is challenged by the limited availability of productive land due to the land conversion issue and, in particular, the leveling-off of rice soil productivity. Acid soils as major contributor to marginal soils occupy approximately 55% of the total terrestrial land in Indonesia. To support the Indonesian policy on food and energy security, acid dryland soil areas have targeted for agricultural land expansion. However, managing such soils for crop productivity with conventional amendments, such as lime was challenged by the availability of lime, its cost and the adverse effects of over-liming. Recent research findings indicate that biochar, with its liming capacity and other beneficial effects, could serve as an amendment to acid soils. A question then can be asked: can biochar be a potential solution for the multiple constraints of Indonesian acid soil? The objectives of this review are to explore the potential of biochar as an amendment to Indonesian acid dryland soils and to develop a research framework for future studies involving biochar so as to support the future of Indonesian food and energy security. Articles and conference papers were selected, studied and critically reviewed. Specific problems with Indonesian acid dryland soils and the utilization of biochar as a potential amendment to the suboptimal soil in Indonesia were investigated. Biochar is alkaline in nature and recent research findings strongly indicate that with its liming effect, water and nutrient retention capability, highly recalcitrant nature, and carbon sequestration capacity could be a potential solution for improving upland acid soil productivity. This could be supported by the huge and sustainable production of feedstock in Indonesia.

Keywords: Ameliorant, liming value, pyrogenic carbon, soil acidity, sustainable agriculture

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INTRODUCTION

The future of Indonesian food and energy security is challenged by the limited availability of productive land due to the high rate of agricultural land conversion (150,000-200,000 ha/year) and, in particular, the leveling-off of rice soil productivity (5.3 t/ha in average) (Badan Pusat Statistik [BPS], 2017). The Indonesian population is estimated to be 319 million in 2045 (BPS, 2017). Assuming that rice consumption per capita is 139 kg/year and wetland productivity is 5.341 t/ha, the total rice consumption should then be 42.381 million tons per year and it requires 9.935 million ha. However, Indonesian rice field area is projected to decrease to approximately 5.1 million ha in 2045 (based on the recent Google Earth's IKONOS, Quickbird, and Worldview with 8 to 12 year time differences) (Mulyani et al., 2016). To overcome the lack of required rice field area, suboptimal soils such as acid soil and climatic dryland soil has being targeted for the future agricultural land expansion (Syakir & Nursyamsi, 2015). The acid soil covers the largest dryland area in Indonesia. It occupies approximately 55% of the total land area (191.09 million ha) in Indonesia. About 107.36 million ha of all Indonesian acid soil~~s~~ is classified as dryland acid soil~~s~~ and the rest (14.93 million ha) as peat soil. Managing acid soils for agricultural land is challenged by the multiple constraints of soil acidity e.g. low pH and cation exchange capacity (CEC), low nutrient concentration and retention (high leaching), low beneficial microbe population, activity and diversity, toxicity of Al, Mn or Fe, high P fixation, and low Mo and other micronutrients.

Liming the soil or adding organic materials are considered the most conventional acid soils amendment strategies in Indonesia. However, there is the potential for over-liming the soil, which lead to adverse effects such as trace element deficiency and cation imbalances, the availability or cost of liming materials, and distribution of liming materials. Adding organic materials to acid soil can increase soil pH and decrease soil exchangeable Al. However, this beneficial effect is only short-lived. Therefore, an alternative solution is required for alleviating the multiple constraints on acid soils for the future agricultural development.

Biochar, the rich C byproduct of biomass pyrolysis under a limited supply of oxygen has being established as a soil amendment and agent of carbon sequestration. It can be produced from a single biomass source or a mixture of biomass materials at the high heat pyrolysis temperature of 300-700°C. Biochar, based on recent research findings, has the liming potential with good pH buffering capacity, thus it could be potential for ameliorating soil acidity. Biochar has also being established as an adsorbent for heavy metal or pollutants removal. Moreover, it also has the capacity to retain water and nutrients, a characteristic that could potentially alleviate the leaching problem of highly weathered tropical acid soils, in addition to as nutrient sources for plant growth. In addition, biochar could also be a secure habitat for soil microbial community due to its high porosity. Biochar has also being established as an agent of carbon sequestration, and greenhouse gas emission abatement, making it a climate change mitigation tool. These beneficial effects of biochar on acid soils have attracted the attention of researchers worldwide and research findings have being formulated to be government policies in some countries. There is a substantial opportunity to alleviate Indonesian soil acidity and climate change problems simultaneously by using biochar. However, there are very limited research findings on ameliorating highly weathered acid soils with biochar in Indonesia. Thus, the objectives of this overview are to summarize the benefits and the potential of using biochar to improve the productivity of Indonesian acid mineral soils and to provide a simplified framework for developing biochar as a sustainable amendment to Indonesian acid mineral soils.

Acid Soils in Indonesia

Acid soils in Indonesia are distributed amongst the big islands, such as Kalimantan (39.42%), Sumatera (28.81%), Papua (18.03%), Java (7.77%), and Sulawesi (6.95%) (Figure 1). Most of the acid soils in Indonesia are derived from old volcanic and sedimentary rocks under a humid tropics condition (annual rainfall > 2.000 mm or udic moisture regime, and temperature $>22^{o}$C), at the wide ranges of their development, and were dominated by order of Ultisols (41.92%), Inceptisols (40.89%), Oxisols (14.14%), Entisols (3.8%), and Spodosols (2.08%) (Mulyani & Sawarni, 2013).

In some sites, such as Jasinga (Bogor, West Java) and Guradog (Lebak, Banten), the exchangeable Al is extremely high (8.7-14.0 cmolc/kg) and the pH is also very low (3.9-4.0) (Berek & Hue, 2016). Consequently, the ameliorant should also

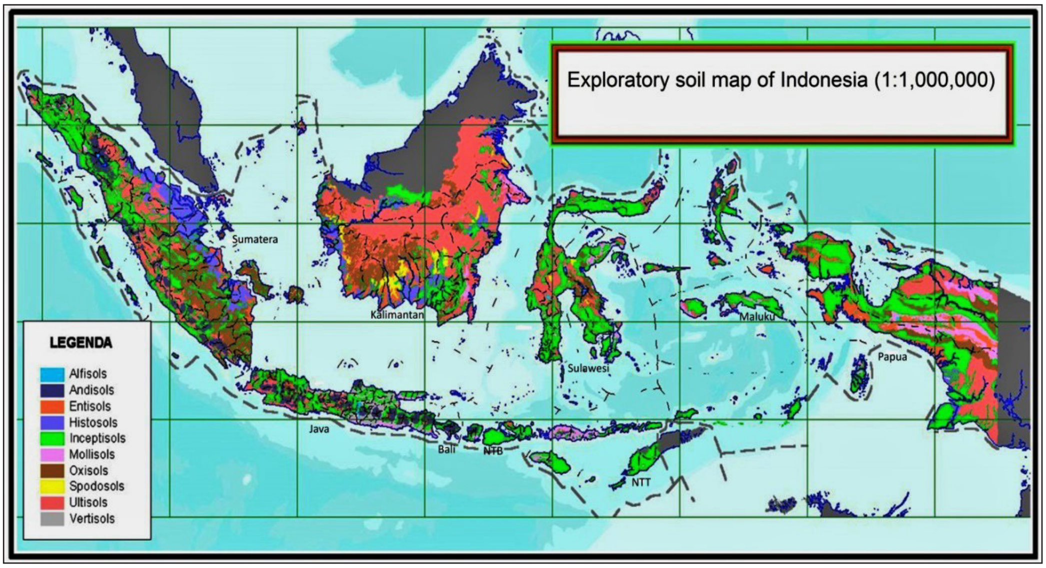

Figure 1. Exploratory soil map of Indonesia (Adapted from Pusat Penelitian Tanah dan Agroklimat Indonesia [Puslittanak], 2000)

be applied at a high rate for increasing the pH and alleviating the toxicity of Al. In addition to chemical constraints, water shortage is another problem of podzolic soils and podsols. The range of critical moisture content is narrow, thus improving water content of these soils could be considered for any amendment chosen (Notohadiprowiro, 1989). Furthermore, the soil acidity issue in Indonesia varies widely site to site. For example, acid soils samples collected from 31 sites (including Java, Sumatera, and Kalimantan) were shown to vary in soil type, dominant clay minerals, C and N content, pH and CEC (Martinsent et al., 2015).

The new challenging for Indonesian food and energy security in the future could be how to improve the productivity of the sub-optimal land, including upland acid soils. Thus, the most important question is: Can biochar help support the future of Indonesian food and energy security?

Biochar Alkalinity, Liming Effect, and pH Buffering Capacity

Biochar is alkaline in nature. The alkalinity of biochar is originated from inorganic and organic components of biochar (Fidel, 2012). More specifically, there are four partitions of biochar alkalinity determined by the quantification method: carbonates, other inorganics, low-pKa organic structural and other organics (Fidel et al., 2017). Carbonate content is responsible for biochar alkalinity (Hass et al., 2012; Mukome et al., 2013) particularly the high temperature pyrolysis biochar (Yuan et al., 2011). The close correlation ($r^2 = 0.84$) between alkalinity and the quantity of basic cations in the biochars has been shown by Fidel et al. (2017), and the carbonate content is closely correlated ($r^2 = 90$) with the quantity of basic cations (Figure 2) (Berek & Hue, 2016). During the pyrolysis, the major basic moieties in the feedstock ash become transformed to their carbonates or oxides, referred to as calcium carbonate equivalent (CCE). The liming value (expressed as the

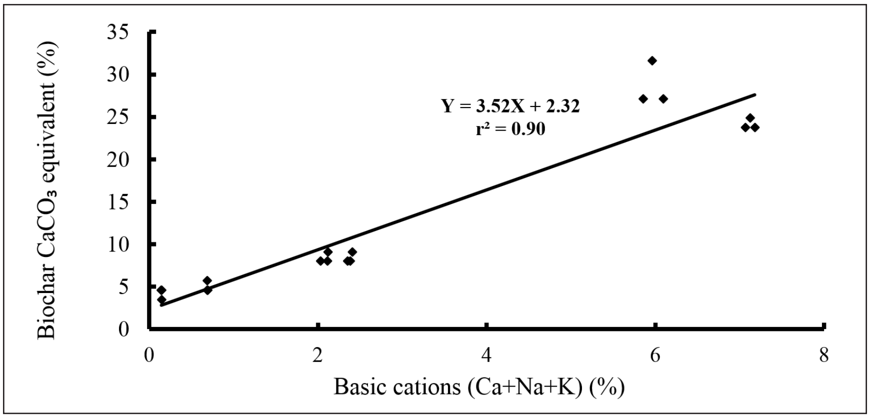

Figure 2. The relationship between biochars $CaCO_3$ equivalent and basic cations (Adapted from Berek and Hue, 2016)

cmol(OH-)/kg biochar) of measured $CaCO_3$ equivalent is then proportional to the liming value or alkalinity that was produced from the total quantity of basic cations in the biochars (Berek & Hue, 2016).

Oxygenic functional groups such as carboxylic acids and phenolics could also be responsible for increasing the alkalinity of low pyrolysis temperature biochar (Keiluweit et al., 2010; Wang et al., 2014; Yuan et al., 2011). The good buffering capacity of the biochars, the capacity of biochars to resist pH change, is originated mostly from their high cation exchange capacity. For example, the negative charge derived from the deprotonation of biochar's surface functional groups and the carbonates give biochars a high buffering capacity (Dai et al., 2014).

Beneficial Effects of Biochar on Acid Soils

A meta-analysis conducted by Biederman and Harpole (2013) revealed that biochar promoted plant productivity and yield allowing for positive short- and long-term effects. For example, biochar's ability to improve water holding capacity and introducing nutrients such as K and P were shown to be short-term effects, while liming effect and nutrient retention were shown to be long-term effects. Alkaline biochar was shown more effective (than acidic one) at increasing soil pH, reducing exchangeable Al and Fe, which in turn, would increase P availability in acid soils. Jeffery et al. (2017) performed a global-meta analysis and pointed out that enhancing crop yield through the use of biochar in the Tropics was more effective than via liming and fertilization of acid low nutrient soils received low fertilizer input. The effects and mechanisms by which biochar can improve acid soil productivity for Indonesian upland acid soils will be summarized and discussed in the following paragraphs.

As previously mentioned, increasing the pH, alleviating Al toxicity and to lesser extent Mn or Fe toxicity, and decreasing P fixation are considered the main expected beneficial effects of adding biochar to acid soils. Figure 3 shows the correlation biochar alkalinity and soil pH, while Figure 4 shows how soil exchangeable Al relates to biochar $CaCO_3$ equivalent. The main beneficial effect of biochar depends on its alkalinity, which is originated from the basic cations in the ash impurity, and the oxygenic surface functional groups attached on its surface (Chintala et al., 2013; Deenik et al., 2011; Joseph et al., 2010; Nguyen & Lehmann, 2009; Novak et al., 2009; Singh et al., 2010; Slavich et al., 2013; Smider & Singh, 2014; Streubel et al., 2011; Tryon 1948; Van Zwieten et al., 2010; Wang et al., 2014; Yamato et al., 2006; Yuan et al., 2011).

Basic cations within biochar are in the form of carbonates or oxides. These cations are the source of biochar alkalinity and will replace the function of lime in producing the ion OH^- to neutralize excess ion H^+ resulting in an increase soil pH (Berek & Hue, 2016). Alleviating Al toxicity may be attributed to the decreased activity of monomeric Al^{3+} and other species by precipitation due to the increased soil pH, the similar mechanism

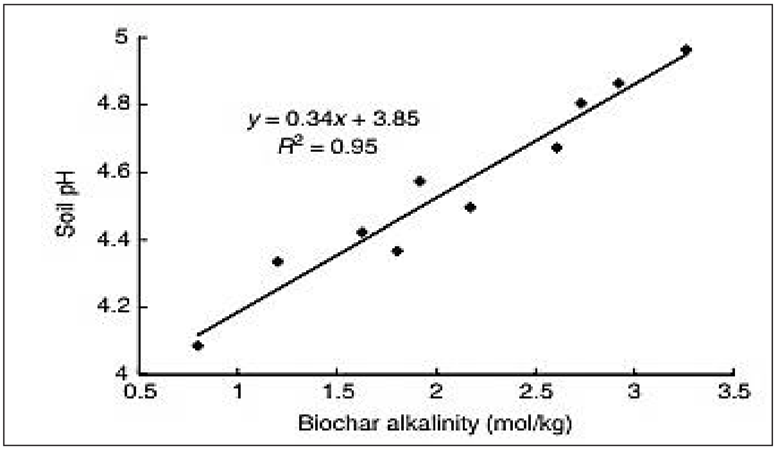

Figure 3. The correlation between biochar alkalinity and soil pH (Adapted from Yuan and Xu, 2011)

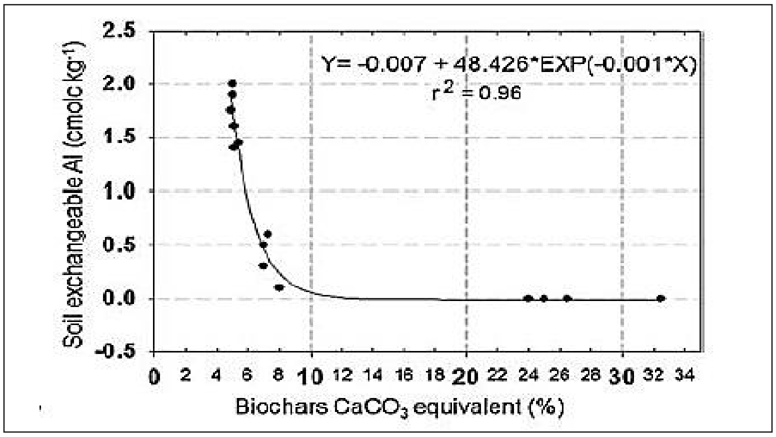

Figure 4. The relationship between soil exchangeable Al and biochars $CaCO_3$ equivalent (Adapted from Berek and Hue, 2016)

by which lime neutralize pH and detoxifies Al phytotoxicity. Increasing soil pH and precipitating Al and Fe will then release fixed P to available form to plant. Micronutrients (e.g., Zn and Mo) will become more readily available, and the activity of beneficial microbes (e.g., rhizobium, mycorrhizal fungi, and phosphate solubilized bacteria) will also become more pronounced after the decrease of soil acidity. Therefore, it seems likely that biochar could replace lime functions in correcting soil acidity problems.

Decarboxylation of organic anions and the negatively charged functional groups will consume protons and increase the soil pH (Wang et al., 2014). The oxygenic functional groups of biochar, such as phenolics and carboxylic acids can provide binding sites for Al adsorption. Carboxylic acids can also complex with Al in the soil solution and reduce its toxicity to plant growth (Figure 5) (Qian et al., 2013). These mechanisms are similar to the mechanisms by which organic amendments alleviating

Al toxicity in acid soils (Berek et al., 1993; Hue, 2011; Hue et al., 1986). Thus, biochar is expected to be more effective than conventional acid soil ameliorants.

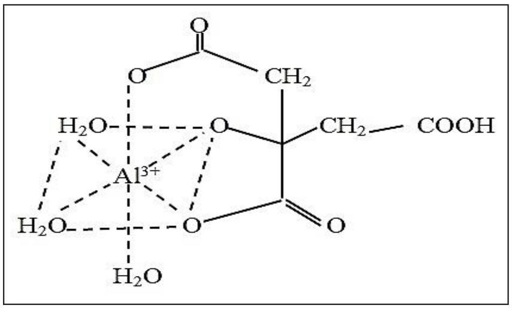

Figure 5. Al-citrate (Adapted from Motekaitis and Mortell, 1984)

Silicon-aluminum interaction (such as the formation of hydroxy-alumino-silicate) has also been shown its positive effect on reducing Al toxicity. For example, the presence of Si in nutrient solution significantly decreased monomeric Al concentration, thus supported corn root elongation (Barcelo et al., 1993). Therefore, another mechanism by which biochar may control highly toxic Al could be through precipitation reaction of Al with silicate or formation of a Al-Si compound in the epidermis root, especially in the Si-rich biochars, such as those from rice straw (Figure 6) (Qian et al., 2016).

Improving soil pH buffering capacity could be another benefit gained through the addition of biochar to low activity/CEC acid soils (Table 1) (Xu et al., 2012). Highly weathered acid soils in the Tropics, such as Oxisols and Ultisols are low in pH buffering capacity due to low CEC and low organic matter, and dominated by kaolinitic and halloysitic minerals, making them prone to soil acidification. Incorporating biochars (with high CEC and pH) into acid soils could make those soils' be more resistant to pH change due to acidification processes (Shi et al., 2017).

Biochar has been shown to be capable of improving water and nutrient retention of soils, including acid soils, in the Tropics. Jeffery et al. (2011) highlighted that one

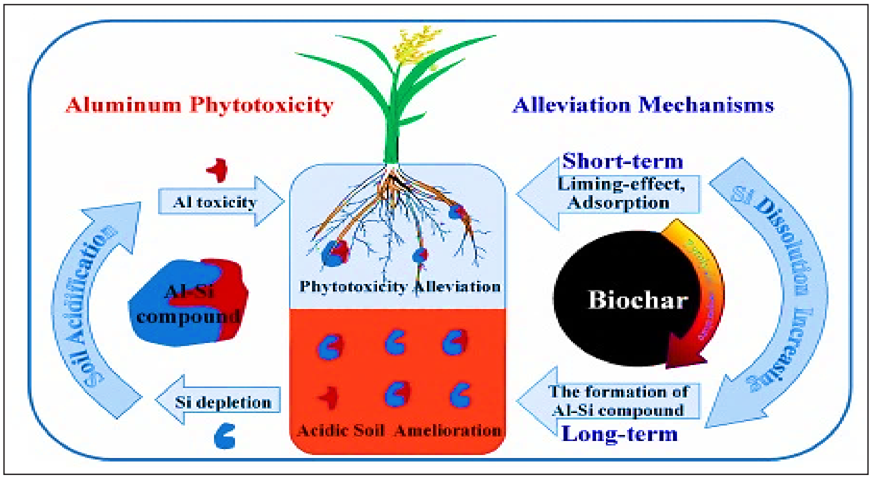

Figure 6. Alleviation mechanisms of Al phytotoxicity using biochar amendment with short-term effects and long-term effects (Adapted from Qian et al., 2016)

Table 1
Effect of two biochars incorporated on properties and pH buffering capacity of soils

Soil and location	Depth (cm)	Treatment	pH	Organic matter (g kg^{-1})	CEC (mmol kg^{-1})	pH buffering capacity (mmol kg^{-1} pH^{-1})
Ultisol from	60-120	Control	5.38	4.4	51.5	20.8
Lizhou,		3% CSBC	6.72	15.5	59.0	22.3
Guangxi		5% CSBC	7.46	23.0	61.7	27.3
		3% PSBC	6.83	27.7	82.6	30.5
		5% PSBC	7.35	41.2	92.8	36.1
Oxisol from	60-130	Control	5.05	8.4	59.7	20.1
Chengmai,		3% CSBC	6.68	19.1	61.2	23.0
Hainan		5% CSBC	7.29	26.3	71.4	27.0
		3% PSBC	6.85	31.0	80.1	29.4
		5% PSBC	7.29	44.4	90.3	38.6
Ultisol from	50-110	Control	5.00	10.9	53.0	15.5
Kunlun,		3% CSBC	6.70	21.4	65.3	18.4
Hainan		5% CSBC	7.47	26.8	70.4	23.6
		3% PSBC	7.04	32.9	78.0	25.7
		5% PSBC	7.45	46.2	96.9	34.6

Note: CSBC = canola straw biochar, PSBC = peanut straw biochar (Adapted from Xu, et al. 2012)

principle mechanism by which biochar enhanced crop yield was its ability to improve soil water holding capacity. High water retention of biochar is mainly attributed to its large surface area and high porosity (Brantley et al., 2015; Brown et al., 2006; Laird et al., 2010; Lua et al., 2004; Novak et al., 2012), which is affected by pyrolysis temperature and feedstock (Brantely et al., 2015; Karhu et al., 2011; Novak et al., 2009, 2012). The extent of which soil water retention is improved by biochar is determined by biochar feedstock, pyrolysis temperature, application rate, and soil properties. For example, adding greenwaste biochar (produced at 450°C by a slow pyrolysis) to an Alfisol increased the field capacity water retained in the soil (Chan et al., 2007). Switch grass biochar, produced at 500°C and applied at 40 Mg/ha, increased water retention of a loamy sand soil more than poultry litter, pecan shell and peanut hull biochars (Novak et al., 2009). Water retention of Hapludoll (from Iowa) was increased by adding a mixed wood biochar (Laird et al., 2010). Water retention of clay soil was improved by adding a mixed tree fruits biochar at 3% (Castellini et al., 2015). Water retention of a loamy sand soil was increased from 13.92% to 17-21.5% through the addition of 5% of biochar made from acacia wood, cashew wood or bamboo (Rattanakam et al., 2017).

Highly weathered soils in the Tropics such as Indonesian acid soils are often poor in nutrients because of leaching. The loss of nutrients not only increases the cost of plant production, but also causes environmental problems such as water pollution. Recent research revealed that adding biochar to soils would decrease nutrient losses (Table 2) (Berek et al., 2018; Berek & Hue, 2016; Laird et al., 2010; Liu et al., 2014; Major et al., 2012; Singh et al., 2010; Ventura et al., 2012). The nutrient retention capacity of biochar could be attributed to its large surface area, high surface charge, high porosity, and other factors such as pH and ionic competition. Thus, adding biochar to acid soils could alleviate soil nutrient losses by electrostatic adsorption and physical entrapment of the nutrients inside the pores (Cheng et al., 2012; Jones et al., 2012; Kameyana et al., 2012; Laird, 2008; Lehmann et al., 2003; Prendergast-Miller et al., 2013).

In addition to improving acid soil productivity, biochar can also act as an agent of carbon sequestration and greenhouse gas (GHG) emission mitigation (Woolf et al., 2010). Biochar can store and lock atmospheric carbon in the soil system on a long-term basis depending on its recalcitrant nature. Biochar may also be reduce GHG emissions, such as N_2O and methane via several pathways (Fidel et al., 2019; Sánchez-García, et al., 2014).

It seems that biochar may not only replace lime or other conventional ameliorants functions in decreasing soil acidity, but also provides a new solution for mitigating climate change problems. Collectively, biochar may be necessary tool in alleviating the Indonesian food and energy security problems for the future.

Biochar Opportunity for Managing Indonesian Acid Soils

To support the Indonesian policy on food and energy security, acid upland soils a component of suboptimal soils has been targeted for agricultural land expansion.

Table 2

Nutrients leached over the 2005 and 2006 rainy seasons under a Colombian savanna Oxisol that received 0 or 20 t/ha biochar in 2002

Depth	Biochar	Total amount leached							
		Water	P	Sr	NH4-N	NO3-N	Ca	Mg	K
m	t ha^{-1}	mm	---------------------------------kg ha^{-1} -------------------------------------						
0.15	0	2823	0.56	0.30b+	9.1b	168.9	61.2b	42.4b	206.9b
	20	2867	0.50	0.98a	69.1a	266.4	227.7a	130.3a	413.6a
0.3	0	2742	0.44a	0.57b	2.7	234.7b	125.4b	84.0	190.1a
	20	2750	0.38b	0.87b	2.2	330.9a	179.3a	92.0	185.9b
0.6	0	2593	0.40	0.41b	1.0b	196.0b	84.6b	55.5b	119.5b
	20	2588	0.36	1.00a	2.4a	399.8a	223.0a	116.7a	131.3a
1.2	0	2361	0.34	0.35a	1.0	110.2a	54.6a	33.5a	36.0a
	20	2346	0.32	0.30b	1.6	108.1b	47.2b	26.1b	24.7b
2.0	0	2329	0.35a	0.06b	0.6a	12.7	6.5b	3.1	14.9
	20	2296	0.26b	0.09a	0.5b	19.8	9.0a	4.3	13.6

Note: + Different letters represent significant differences (P<0.00t; n = 3) between treatents at a single depth. No letter indicates that differences are not significant (only flux dominated bu unsaturated flow) (Adapted from Major et al., 2012)

This opens up opportunities for biochar to be developed as a sustainable amendment to acid soils and an agent of climate change mitigation. This opportunity was also being supported by the ever-increasing research interest of Indonesian scholars and research agencies, such as the Indonesian Agency of Agricultural Research and Development (Balitbangtan) Ministry of Agriculture, the Indonesian Agency of Forestry Research and Development (Balitbanghut), and Indonesian Biochar Association (ABI) which was established several years ago.

A sustainable and available supply of feedstock is an essential requirement for biochar development. There are potential feedstocks for biochar that are available in abundance in Indonesia include palm oil empty fruits and kernels, sugar cane waste, sawdust, rice husks, sewage sludge, manures and urines mixtures, and municipal waste. Utilization of waste, municipal waste in particular, as a potential biochar feedstock could be a comprehensive solution from environmental, health, climate change mitigation, and agricultural perspectives.

Economic and socially viable and acceptance of biochar technology could be a noble chance for Indonesia small-scale farmers as a way out to face with the high cost and the decreased availability of fertilizer and other conventional amendments in rural areas. Most of Indonesia farmers experiencing the benefit of slash and burn traditional practices that provide short-term high yield resulted from the basic nutrient content in the ash. In many parts of this country, people produce charcoal for energy purposes. Therefore, this could also be the opportunity for biochar development in respect to the familiarity of the community to the production process.

Future Perspective

Initial biochar research reports, such as Berek and Hue (2016), Islami et al. (2011), Martinsen et al. (2015), Masulili et al. (2010), Sukartono et al. (2011) and Yamato et al. (2006) indicated that biochar could be potential as an amendment for Indonesian acid soils. Therefore, future research needs to be developed in Indonesia on improving soil productivity, increasing crop yield, and climate change abatement through the incorporation of biochar in acid soils. Thus, a research framework is required to be designed for researchers to go through. As previously mentioned, managing acid upland soils in Indonesia will be challenging due to the multiple constraints that vary from site-to-site. For example, acid upland soils and the availability of feedstock are widely distributed among the islands and even on the same island.

To overcome these high variability circumstances, a specific biochar system for Indonesian acid soils could be developed perhaps based on the engineered/designer biochar concept. The potential Indonesian biochar feedstock needs to be mapped, followed by establishing the production pathways. Next, the characterization of the products-biochars based on a general or local standard for acid soils that should be performed. Then, conducting pot/greenhouse and field trials are necessary to test the biochar effects on soil properties, carbon sequestration, greenhouse gases emission, and plant growth and yield. The conceptual biochar research priority and framework for Indonesian acid soils is illustrated in Figure 7.

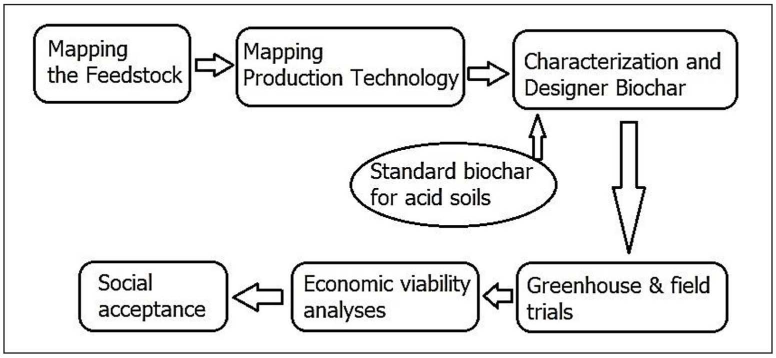

Figure 7. A simplified biochar research priority and a framework for Indonesian acid soils

CONCLUSION

Biochar has tremendous potential as an alternative solution for amending soil acidity, which in turn, will support the future of Indonesian food and energy security. The abundance availability of biochar feedstock, its wide distribution, cheaper production technology, high research interest, and familiarity within the community for product utilization, are all-significant opportunities for biochar development in Indonesia.

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