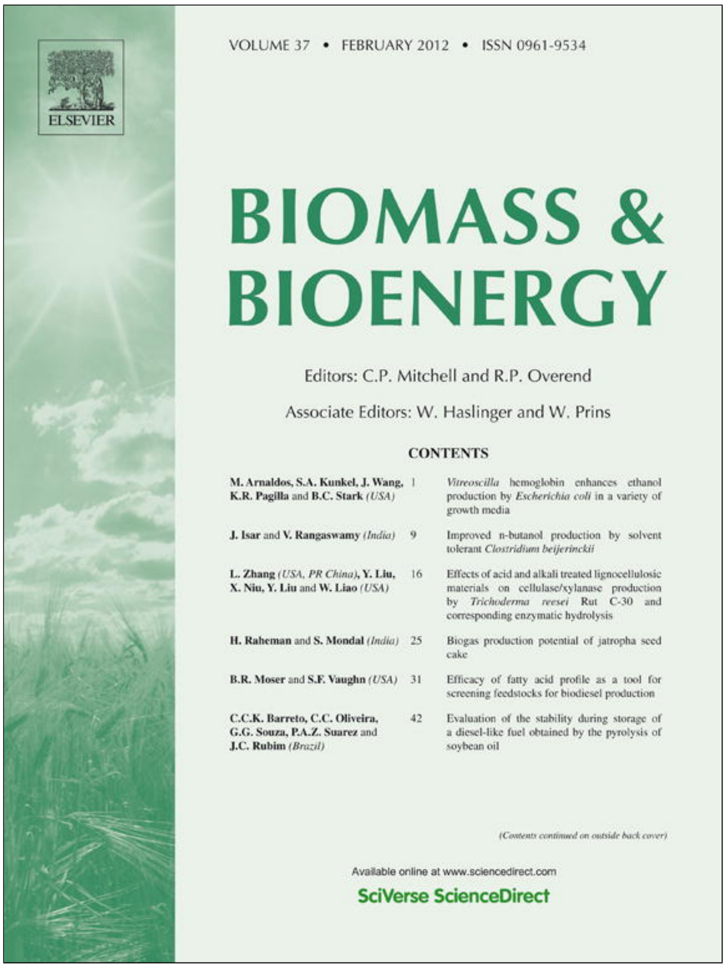

VOLUME 37 • FEBRUARY 2012 • ISSN 0961-9534

ELSEVIER

BIOMASS & BIOENERGY

Editors: C.P. Mitchell and R.P. Overend

Associate Editors: W. Haslinger and W. Prins

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BIOMASS AND BIOENERGY 37 (2012) 161–168

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Comparison of kiln-derived and gasifier-derived biochars as soil amendments in the humid tropics

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ARTICLE INFO

Article history:
Received 3 December 2010
Received in revised form
10 December 2011
Accepted 13 December 2011
Available online 30 December 2011

Keywords:
Biochar
Pyrolysis
Gasification
Tropics
Soil pH
Ash

ABSTRACT

Biochar is the carbonaceous solid byproduct from thermal treatment of biomass that is produced specifically for application to soils. Studies have shown that when biochar is added to soils, it is able to increase yields, improve soil properties, and effectively store carbon for hundreds to thousands of years. This study compared the performance of biochar from five different feedstocks (coffee husks, maize cobs, eucalyptus wood, groundnut shells, and rice husks) produced in a traditional kiln and biochar from two different feedstocks (maize cobs and eucalyptus wood) produced in a downdraft gasifier. This research, conducted at Makerere University in Kampala, Uganda, was aimed at investigating the potential of biochar as a soil amendment in the humid tropics. Biochar samples were combined with undisturbed soil in a 45-day pot experiment to compare effects on maize growth. On average, soils amended with gasifier-produced biochar had higher yields than the unamended soil and soils amended with kiln-produced biochar. Comparing kiln-produced chars from different feedstocks, the coffee husk chars were the most productive. Results indicated that the soluble ash content of the biochar had the greatest influence on soil productivity. Ugandan soils, like most soils in the humid tropics, are strongly acidic (pH = 4.7), and the increase in pH caused by the soluble ash in the biochar provided for more favorable growing conditions and higher nutrient availability.

1. Introduction

Biochar is the carbonaceous solid byproduct from heating biomass in the absence of oxygen. Traditionally known as charcoal when produced for fuel, the name biochar is used when the material is produced specifically for application to soil as a part of an agronomic or environmental management program [1]. When biochar is used as a soil amendment, crop yields and productivity improve, soil acidity decreases, and the need for some chemical and fertilizer inputs decreases [2]. Biochar can also improve surface and ground water quality by aiding in soil retention of nutrients and agrochemicals, thereby reducing run-off and soil leaching [3]. Additionally, biochar can reduce greenhouse gas emissions from soils [4-6].

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doi:10.1016/j.biombioe.2011.12.017

Biochar's ability to retain plant carbon in a stable state for hundreds to thousands of years allows for energy derived from a biochar production process to be carbon-negative [7].

A variety of thermal processes can be used to create biochar [1]. The most common and most studied method has been the use of a traditional mound or pit kiln. In this pyrolysis process, the primary product is charcoal for use in heating or cooking applications [7]. More generally, pyrolysis can generate a variety of liquid, solid, and gaseous products depending on the heating rate and reaction temperature. Under some conditions, pyrolysis produces significant quantities of liquid or gas that can also be used as energy carriers. For example, fast pyrolysis yields up to 750 g kg^{-1} of bio-oil, a liquid mixture of organic compounds that can be used as boiler fuel or upgraded into transportation fuels or other chemical products [8]. Gasification, which uses elevated temperatures and moderate heating rates, yields a flammable producer gas composed primarily of carbon monoxide and hydrogen. Producer gas can be burned directly for heating applications, used to produce power from an internal combustion engine or turbine, or chemically converted to other products such as transportation fuels [9].

Gasification is not considered to be an effective method of producing biochar because a well-designed gasifier converts only 50 g kg^{-1} of the biomass feedstock into biochar. Nevertheless, biomass gasifiers are often built at relatively large scales compared to traditional kilns and cook stoves, and can consume up to a few hundred Mg of biomass per day, resulting in several Mg of biochar per day. It would require over ten thousand cook stoves to generate an equivalent amount of biochar. The conditions under which biochar is produced during gasification are distinct from other methods of producing biochar, which justifies an evaluation of the agronomic performance of gasification-derived biochar.

This study was designed to directly compare kiln-produced biochars and gasifier-produced biochars in a plant growth experiment using a traditional charcoal feedstock: eucalyptus wood, as well as locally available agricultural wastes: coffee husks, maize cobs, groundnut shells and rice husks. These feedstocks were chosen due to their wide availability in Uganda and throughout the humid tropics, and for their differences in physical composition. Two batches of biochar were made for each feedstock in order to investigate the consistency of the production methods. The rate of biochar used to amend the soil was chosen such that approximately 10 g kg^{-1} of carbon was added to the soil (assuming the biochar contained 500 g kg^{-1} carbon). At this rate, Rondon, Ramirez, and Lehmann [10] showed biochar additions produced significant increases in plant biomass yield along with reductions in NO_x and methane emissions.

2. Material and methods

2.1. *Materials*

Biomass samples were obtained domestically in Uganda, directly from local farmers who had harvested the biomass by hand. These samples were transported to Makerere University by truck and stored for up to a month in a secured, open-air shelter on the university campus. Eucalyptus wood chunks (*Eucalyptus grandis*) were cut from timber in the western part of the country (Kyenjojo District, Toro Sub-region) that was approximately 10 years old. All other biomass was obtained at the end of that species' production cycle as a waste byproduct. Maize cobs (*Zea maize*) and rice husks (*Oryza sativa*) were obtained in Iganga town (Iganga District, Busoga Sub-region). Coffee husks (*Coffea arabica*) were obtained in Masaka town (Masaka District, Buganda Sub-region). Groundnut shells (*Arachis hypogaea*) were obtained in Soroti town (Soroti District, Teso Sub-region). Except for the eucalyptus, which had all bark removed before use, the biomass samples were used in their entirety as received (properties listed in Table 1).

2.2. *Char production*

A total of 14 biochar samples were created at Makerere University using a kiln built for this research and a gasifier used for research at the university. Two batches of kiln-produced biochar were obtained from each of eucalyptus wood, coffee husks, maize cobs, groundnut shells and rice husks. Similarly, two batches of gasifier-based char were produced from eucalyptus and maize cobs.

The kiln was based on a common two-barrel design as shown in Fig. 1. The smaller barrel, approximately 20 cm in diameter and 35 cm tall, contained the biomass (1–4 kg, depending on biomass density) and was placed upside down inside the larger barrel. The larger barrel, approximately 40 cm in diameter and 50 cm tall with holes cut around the bottom for added airflow, held fuel (domestically produced charcoal) that surrounded the smaller barrel. A fire was started in the larger barrel and maintained for 60 min, after which the fire was allowed to extinguish (no more fuel was added). The kiln was then allowed to cool for 60 min before it was opened and the biochar was removed. The highest estimated temperature reached inside the kiln was between 400 and

Table 1 – Proximate analysis results for biomass samples used to produce biochars. Moisture reported on a wet basis; all other values reported on a dry basis.

Biomass	Moisture (g kg^{-1})	Volatiles (g kg^{-1})	Fixed C (g kg^{-1})	Ash (g kg^{-1})
Eucalyptus	78	848	143	9
Maize cobs	71	770	216	14
Coffee husks	123	675	267	59
Rice husks	77	611	144	245
Groundnut shells	76	742	244	13

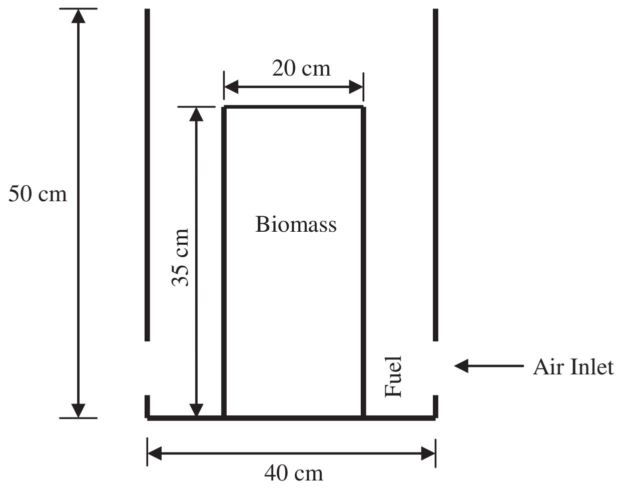

Fig. 1 – Schematic of double-barrel kiln built to produce slow pyrolysis chars.

600 °C at the top and between 600 and 800 °C at the bottom. Biochar yields were 140–290 g kg^{-1} of the initial biomass weight for eucalyptus, 240–250 g kg^{-1} for maize cobs, 450–490 g kg^{-1} for rice husks, 360–430 g kg^{-1} for coffee husks, and 290–320 g kg^{-1} for groundnut shells.

The gasifier was a basic, suction-based, downdraft gasifier (Svedlunds Gasgenerator AB). Fig. 2 provides a schematic illustration of the device. The gasifier held approximately 0.5 m^3 of starting material and operated between 800 and 1000 °C; internal temperatures were estimated from temperature gun readings of the gasifier exterior and literature values from experimentation with similar units [11]. The gasifier was intended to be operated without any start-up charcoal, but initial test runs showed this was not possible (sufficient flammable gas to maintain a flame could not be produced). To address this issue, charcoal from the test feedstock, produced using the kiln prior to the run in the gasifier, was used to achieve the initial firing. Each run lasted 2–3 h and was considered successful if a self-sustaining flame was maintained at the gas outlet for at least half of the run time. Biochar yields were between 60 and 70 g kg^{-1} of the initial biomass weight for eucalyptus and 50 and 80 g kg^{-1} for maize cobs.

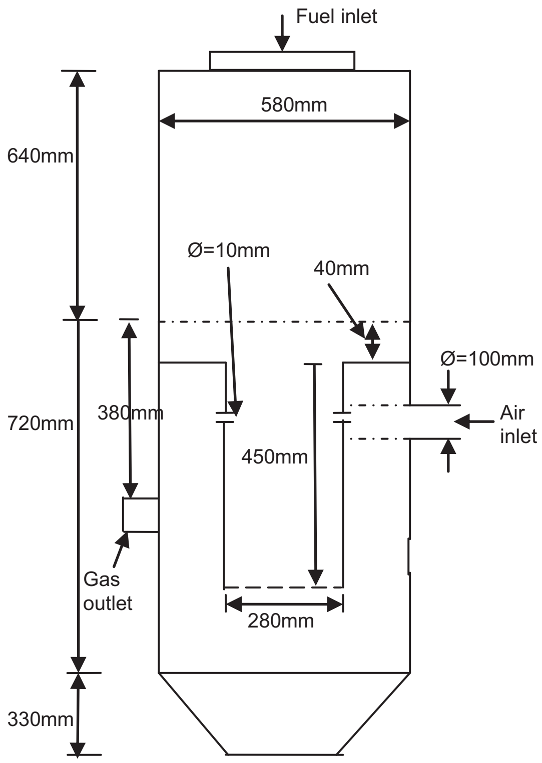

Fig. 2 – Schematic of down-draft gasifier at Makerere University used to produce gasification biochars.

Initial feedstock mass for gasification was measured using an analog hanging scale (0.5 kg precision); all other weight measurements were made with a Mettler PC 4400 digital balance (0.01 g resolution). Temperatures were measured using a laser-guided infrared RayTek temperature gun (Santa Cruz, CA).

2.3. *Greenhouse study*

Soil for the 45-day plant growth study was a clay loam (36% sand, 22% silt, 42% clay) obtained from an undisturbed field located at Makerere University Agricultural Research Institute at Kabanyolo (0°20′23″ N, 32°36′10″ E). Soil properties are listed in Table 2.

For each pot, biochar was combined with soil at a ratio of 20 g of biochar to 1 kg of soil. Ten replicates (five each for each production batch of biochar) were created for a total of 80 pots including the control pots without biochar addition. Maize (*Zea maize L.*, Longe 5) was used as the test crop. Four seeds were sown in each pot and plants were thinned to two per pot after watering on day 12. Weeds in pots were removed manually. Initially, fertilizer was applied to all pots with an application rate of 60 kg ha^{-1} of nitrogen and 45 kg ha^{-1} of P_2O_5, the recommended rates for Ugandan soils [12]. A second round of nitrogen fertilizer in the form of diluted urea was applied at a concentration of 125 mg L^{-1} after yellowing and wilting of the lower leaves was observed on day 28. This application was spread over two watering periods on day 36 and day 37 of the experiment, and provided approximately 30 kg ha^{-1} of additional nitrogen to the plants.

Pots were arranged in a completely randomized design in a screen-covered greenhouse (located at 0°20′03″ N, 32°33′57″ E), with the exception that all pots amended with biochars from the first production batch were on one side of the greenhouse and all the pots amended with biochars from the second production batch were approximately 2 m away on the other side of the greenhouse. The greenhouse was open to the atmosphere, so temperature and relative humidity could only be monitored. Temperatures ranged from 39 °C to 15 °C with an average daily high of 33.4 °C and an average low of 17.6 °C. Relative humidity ranged from 11% to 100% and averaged 64%.

Plant growth was tracked during the pot experiment by taking measurements of height, leaf width and leaf length on day 15, day 30, and day 45. After day 15, qualitative observations showed that the height measurement did not necessarily reflect the true biomass yield of the plants. To compensate, an additional stem diameter measurement was taken on days 30 and 45 so that stem volume could be calculated. At the end of the 45 days, plants were cut and weighed

Table 2 – Soil fertility properties of clay loam soil used in pot study.

pH	Organic matter ($g\,kg^{-1}$)	Total nitrogen ($g\,kg^{-1}$)	Plant-available phosphorus ($mg\,kg^{-1}$)	Ca	Mg	K	Na	Cation exchange capacity
				mmol kg^{-1} of soil				
4.7	26.9	1.2	8.22	38	10.2	5.1	0.8	168

to obtain a wet weight. A representative sample of plants was then dried for four days at 60 °C to obtain the dry weight. Additionally, two randomly selected pots from each set of five were analyzed for soil pH; one pot from each set was analyzed for soil cation exchange capacity (CEC) and exchangeable acidity. Soil pH was measured potentiometrically using soil-water suspensions (10 g soil in 25 ml of distilled water) after a 30 min equilibration time. Potential cation exchange capacity was measured by an ammonium acetate leaching method. Soil (5 g) was leached at a rate of 30 drops per minute with a 1:1 ratio of 1 mol L^{-1} ammonium acetate/ethanol solution. Samples were then saturated with sodium acetate, washed with ethanol, and leached again with 1 mol L^{-1} ammonium acetate. Sodium concentration in the leachate was determined by flame photometry.

2.4. Material characterization

Proximate analysis was performed on each feedstock and biochar sample according to ASTM Standards E1755-01 and D1762-84, respectively [13,14]. A slightly lower temperature (575 °C) was used to estimate the volatile matter content of the biomass samples. Insoluble and soluble ash content of the biochars were determined by Control Laboratories (Watsonville, CA); ash formed after combustion at 550 °C was digested with hydrochloric acid (6 mol L^{-1}) to remove soluble ash and the remaining insoluble ash samples were rinsed, dried and weighed.

2.5. Statistical analysis

Statistical significance was determined using one-way ANOVA and Tukey's Honestly Significant Difference (HSD) test methods ($n = 10$ for plant growth and $n = 4$ for soil pH, $\alpha = 0.05$).

3. Results and discussion

3.1. Biochar characterization

Averaged and individual batch proximate analysis and soluble ash content results for the produced biochars are listed in Table 3. Gasifier-produced biochars had higher ash contents than kiln-produced biochars from the same feedstock; biochar yields from gasification are lower and nearly all of the mineral matter (ash) became concentrated in the solid co-product. Gasifier-produced biochars also exhibited more variability in properties compared to kiln-produced biochars from the same feedstock. Although similar procedures were followed for the creation of all biochars, the dynamic nature of the gasification process and the limited amount of control possible on the simple gasification equipment available at Makerere University resulted in no two runs undergoing the exact same conditions.

3.2. Plant growth

Plant growth results from the test crop are shown in Tables 4 and 5, and include plant height, stem volume, leaf area and cut dry weight from days 15, 30 and 45. Table 4 provides a comparison between soils amended with gasifier-produced biochars and soils amended with kiln-produced biochars. Soils amended with gasifier-produced biochars exhibited more maize growth than soils amended with kiln-produced biochars from the same feedstock. Table 5 provides a comparison of kiln-produced biochars made from different feedstocks. Soils amended with coffee husk biochar exhibited the greatest maize growth while the unamended control soils and the soils amended with eucalyptus wood and groundnut shell biochars exhibited the least growth.

It was observed that the maize plants grew unusually tall in the greenhouse compared to plants grown in the field. This extra height was noted in all of the plants whether the soils had been amended or not. As an open-air, screened greenhouse, the maize would have been exposed to the same humidity and temperature conditions as plants outside the greenhouse. One possibility for the unusual vertical growth is that the plastic covering of the greenhouse acted as a light filter, limiting the amount of light that was able to penetrate and causing the plants to grow upwards in search of unfiltered light (Professor Randy Killorn, emailed personal communication, 2009 April 8). A pyronometer was used to measure the incident radiation immediately outside and inside the greenhouse, giving values of 750–850 W m^{-2} and 400–600 W m^{-2}, respectively, thus supporting the limited light explanation. As all maize plants were exposed to the same conditions, it is not believed that the lighting impacted the comparisons between the biochar amendments.

3.3. Soil properties

Table 6 lists the pH, CEC and exchangeable acidity of unamended and biochar-amended soils after the 45-day growth study. The pH of the control soil and some of the biochar-amended soils decreased during the pot experiment compared to the starting soil (pH = 4.7), most likely due to the application of nitrogen fertilizer several days into the experiments. Urea ($CO(NH_2)_2$) undergoes mineralization in the soil to form ammonium (NH_4^+) then nitrate (NO_3^-) ions through

Table 3 – Proximate analysis results for biochars used as soil amendments. Moisture values reported on a wet basis; all other values reported on a dry basis. Soluble ash was determined by dissolution in hydrochloric acid (6 mol L^{-1}) after char combustion at 550 °C. Batch, biochar production batch; ND, not determined (due to small sample size).

	Feedstock	Batch	Moisture (g kg^{-1})	Volatiles (g kg^{-1})	Fixed C (g kg^{-1})	Ash (g kg^{-1})	Soluble ash (g kg^{-1})
Gasifier	Eucalyptus	Average	52	63	816	121	27
		1	63	62	867	71	25
		2	42	64	766	170	28
	Maize cobs	Average	45	68	370	562	112
		1	37	49	318	633	102
		2	52	86	424	490	122
Kiln	Eucalyptus	Average	27	198	783	19	
		1	29	217	764	19	ND
		2	25	179	802	19	11
	Maize cobs	Average	31	170	692	138	
		1	30	91	808	101	ND
		2	31	249	577	174	69
	Coffee husks	Average	60	233	606	160	156
		1	64	266	580	154	146
		2	56	201	632	167	165
	Rice husks	Average	27	85	210	524	14
		1	28	113	380	506	16
		2	25	57	41	542	13
	Groundnut shells	Average	44	130	736	134	79
		1	44	104	756	140	84
		2	44	155	716	128	73

nitrification. Application of nitrogen can result in a marked decrease in soil pH in poorly buffered soils as protons are released during the nitrification process. For biochar-amended soils, some had significantly higher pH values at the end of the study (pH = 5.5 and 5.4 for coffee husk kiln biochar and maize cob gasifier biochar, respectively) while others had pH values similar to those of the unamended soils (pH = 4.3 for both eucalyptus wood and rice husk kiln biochars).

Addition of biochars slightly increased the soil's cation exchange capacity (CEC). This increase was greatest for kiln-produced coffee husk and maize cob biochars. The control soil's CEC of 168 mmol kg^{-1} soil was already relatively high and increases in CEC in the biochar-amended had little noticeable effect on plant growth. With the exception of groundnut shell and eucalyptus kiln biochars, addition of biochar decreased the soil's exchangeable acidity. Soils amended with coffee husk kiln biochar and the two gasifier biochars exhibited the greatest decrease, reducing the exchangeable acidity by about half.

3.4. *Relationship between biochar ash content and plant growth*

Based on maize biomass production, gasifier-produced biochar appears to be a more effective soil amendment than kiln-produced biochar derived from the same feedstock; likewise, coffee husk and maize cob derived kiln biochars appear to be more effective soil amendments than those derived from eucalyptus, groundnut shell, and rice husk. We attribute this difference to the changes in soil pH and exchangeable acidity

Table 4 – Plant growth measurements of maize grown on unamended soil and soil amended with kiln or gasifier-produced biochar from eucalyptus or maize cobs. Values from the same sampling date followed by different letters are significantly different ($n = 10$, $p < 0.05$) according to Tukey's honestly significant difference test.

Day	Unamended soil control	Kiln – eucalyptus	Gasifier – eucalyptus	Kiln – maize cobs	Gasifier – maize cobs
Height (cm)					
15	12.5 a	12.4 a	13.2 a	12.9 a	13.8 a
Stem volume (cm^3)					
30	13.0 d	12.5 d	17.9 c	20.7 b	27.3 a
45	27.1 d	24.0 d	32.6 c	37.9 b	49.3 a
Leaf area (cm^2)					
15	37.1 c	40.0 abc	44.1 a	36.4 c	41.7 ab
30	60.5 c	58.2 c	75.6 b	74.1 b	95.2 a
45	87.5 c	88.5 c	103.9 b	113.4 a	115.9 a
Cut plant dry mass (g)					
45	6.23 d	5.95 d	7.47 c	8.33 b	10.32 a

Table 5 – Plant growth measurements of maize grown on unamended soil and soil amended with kiln-produced biochar from different feedstocks. Values from the same sampling date followed by different letters are significantly different ($n = 10$, $p < 0.05$) according to Tukey's honestly significant difference test.

Day	Unamended soil control	Eucalyptus	Maize cobs	Coffee husks	Rice husks	Groundnut shells
Height (cm)						
15	12.5 a	12.4 a	12.9 a	12.2 a	12.9 a	11.8 a
Stem volume (cm^3)						
30	13.0 d	12.5 d	20.7 b	22.9 a	15.7 c	11.9 d
45	27.1 d	24.0 d	37.9 b	44.2 a	31.1 c	24.8 d
Leaf area (cm^2)						
15	37.1 b	40.0 ab	36.4 b	37.9 ab	42.3 a	37.2 b
30	60.5 d	58.2 d	74.1 b	76.9 ab	81.4 a	67.1 c
45	87.5 c	88.5 c	113.4 a	116.9 a	114.8 a	96.8 b
Cut plant dry weight (g)						
45	6.23 d	5.95 d	8.33 b	10.19 a	7.63 c	6.07 d

associated with the soluble ash content in the biochars as shown in Figs. 3–6.

When ash in biochar is exposed to water, the soluble components ionize, creating hydroxide ions and thereby raising the soil pH and lowering the exchangeable acidity. The control soil had a pH of 4.7 at the beginning of the study, which would be considered strongly acidic. At such levels of acidity, trace elements become soluble and available to plants. One of these elements, aluminum, is toxic to plants in low concentrations [15]. A slight rise in soil pH as a result of the

Table 6 – Soil pH, cation exchange capacity (CEC) and exchangeable acidity of control and biochar-amended soils at the termination of the growth study after 45 days. Soil pH values followed by different letters are significantly different ($n = 4$, $p < 0.05$) according to Tukey's honestly significant difference test.

	Treatment	pH	CEC (mmol kg^{-1} of soil)	Exchangeable acidity (as H+, mmol kg^{-1} of soil)
	Control soil	4.0 e	172	81
Gasifier – produced	Eucalyptus	5.0 ab	173	45
	Maize cobs	5.4 a	173	23
Kiln – produced	Eucalyptus	4.3 d	172	99
	Maize cobs	4.6 c	183	73
	Coffee husks	5.5 a	192	38
	Rice husks	4.3 d	177	71
	Groundnut shells	4.7 bc	173	87

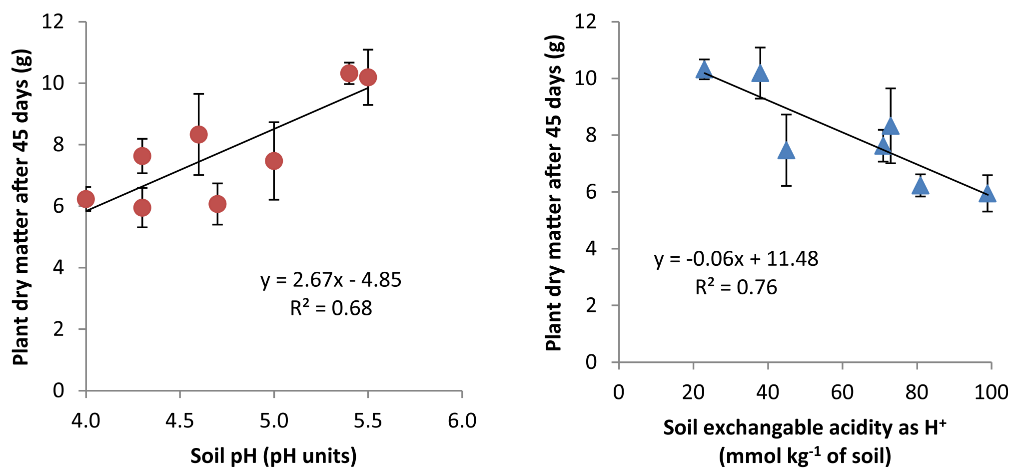

Fig. 3 – Relationship between soil properties and maize growth on biochar amended soils after 45 days. Error bars represent 95% confidence intervals ($n = 4$).

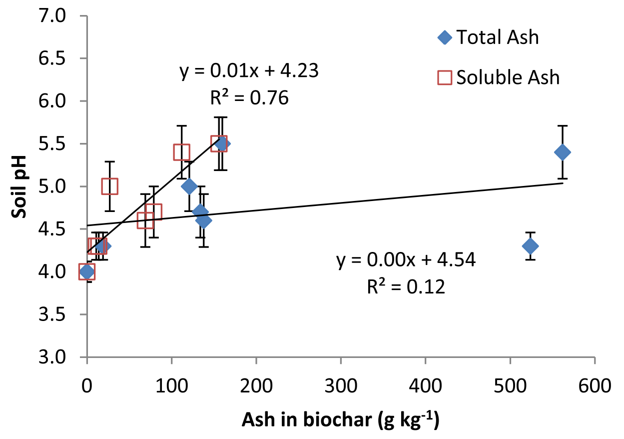

Fig. 4 – Relationship between soil pH and biochar ash content for biochar amended soils after 45 days. Error bars represent 95% confidence intervals ($n = 4$).

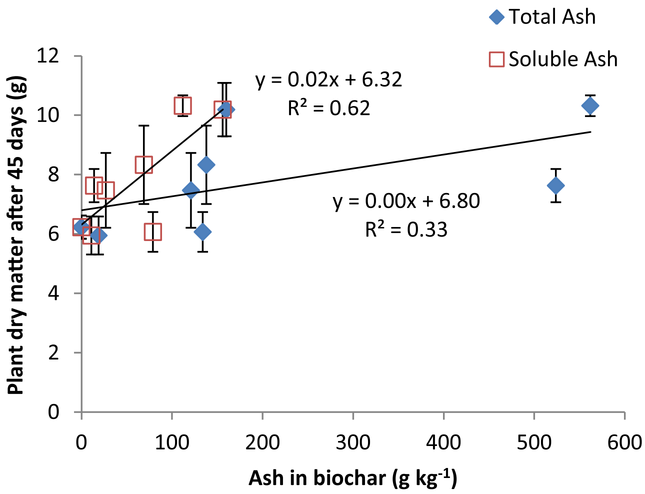

Fig. 6 – Relationship between plant growth and biochar ash content for maize grown on biochar amended soils for 45 days. Error bars represent 95% confidence intervals ($n = 10$).

ash content in the biochars could substantially reduce the amount of available aluminum. Fig. 3 shows an increase in plant growth with the increase in pH and decrease in acidity, suggesting that soil acidity was a limiting factor for plant growth for this soil.

Soluble ash content appears to be a better indicator of that biochar's effect on soil properties than the total ash content. Some feedstocks, such as rice husks, contain large amounts of silica, which, when treated with heat, produce chars with high total ash contents but low soluble ash contents [16]; the ash fraction of these biochars is expected to be relatively inert with respect to soil chemistry. Figs. 4 and 5 show the relationships between biochar ash content and soil pH increases and exchangeable acidity decreases, respectively, observed in this study; there is much stronger evidence for a correlation between soluble ash content and these soil properties than for a total ash, especially with respect to soil pH. Fig. 6 presents a correlation between biochar soluble ash content and plant dry matter after 45 days. This relationship seems to hold except for plants grown on soil amended with groundnut shell biochar; removing that data point (79, 6.07) results in a trend line of $y = 0.027x + 6.50$ and $R^2 = 0.87$. The reason for the apparent deviation of the groundnut shell biochar is not known and may warrant future study. It is speculated that the reason cation exchange capacity did not appear to be a factor was that the biochar soluble ash content increased the base saturation of the soils, even if the overall CEC was relatively unaffected. Base saturation refers to the fraction of basic cations, especially K^+, Na^+, Ca^{2+} and Mg^{2+}, occupying exchange sites, and therefore being available and beneficial to plants. These replace some of the cations in soils that are less useful or even harmful to plant growth, such as aluminum [17].

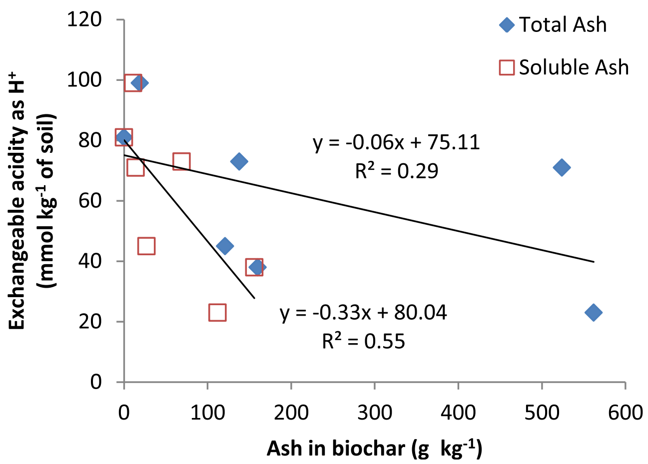

Fig. 5 – Relationship between soil exchangeable acidity and biochar ash content for biochar amended soils after 45 days ($n = 2$).

3.5. *Potential concerns with gasifier-produced biochar application*

Some concern has been expressed about the use of gasification chars as biochars due to their low carbon contents, high ash contents, and potential to contain plant growth-inhibiting allelochemicals such as polycyclic aromatic hydrocarbons (PAHs) [18]. For example, Rogovska et al. [18] found that corn seedling growth was slightly inhibited when grown in water extracts of high temperature (750–850 °C) switchgrass and corn fiber gasification chars. In this experiment, soils amended with the gasifier-produced biochar were more productive (higher biomass dry matter production during growth study) than the unamended controls or the soils amended with kiln-produced biochar, suggesting that if there were inhibitory compounds present in the gasifier-produced chars, the effects of these compounds were overwhelmed by the positive effects caused by the increase in soil pH and decrease in soil exchangeable acidity.

4. Conclusions

Biochar produced by gasifiers and kilns can be an effective soil amendment in the humid tropics where the acidic, weathered nature of the soils presents challenges to crop growth.

Gasifier-produced biochars may be better suited for application than kiln-produced chars due to their higher ash content and ability to mitigate soil acidity.

Biochar could increase the overall value of a gasification energy platform in the humid tropics by providing a co-product can be used to add value to poor soils. This is especially applicable to distributed small-scale gasification projects in developing countries. The biochar byproduct from a small community-based gasifier could be mixed into soils, especially those with low pH, to increase soil productivity and provide an opportunity to qualify for carbon sequestration credits available from international carbon markets.

Application of biochar in the developing world must be pursued with caution. Problems arising from high soil acidity and the potential for nitrogen deficiency in the humid tropics may result in kiln-produced biochar not producing the desired results. Additionally, biochar is not intended to be used alone but rather in combination with fertilizers (organic or inorganic) which provide necessary plant nutrients; without such fertilizers, biochar application may have little effect. If a biochar implementation program were poorly planned and failed, the negative consequences could seriously undermine future attempts at integrating biochar use within development projects. Thus, field-scale trials should be conducted prior to any wide-spread application of biochar in the humid tropics.

Acknowledgements

One of the authors (CD) was sponsored by the Rotary Foundation to conduct this study in Uganda. Additionally, he expresses his gratitude to the professors at Makerere University for making this research possible, especially the support of Dr. Izael Pereira Da Silva and the Centre for Research in Energy and Energy Conservation, located at the Faculty of Technology at Makerere University. One of the authors (CEB) wishes to acknowledge the support of the National Science Foundation of the United States towards her participation in this project. One of the authors (MAEO) wishes to acknowledge the support of the Swedish International Development Cooperation Agency (SIDA) for setting up the gasifier research facility and Professor Björn Kjellström of Luleå University of Technology for facilitating the donation of the gasifier.

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