IMPACT OF BIOCHAR APPLICATION ON THE CHEMICAL PROPERTIES OF ACIDIC AND NEUTRAL SOIL

Abstract

The purpose of this research was to study the impact of biochar application on soil pH and chemical properties in both acidic and neutral soils. Three types of biochars were used in a greenhouse experiment: 1) red gram straw biochar produced at 400°C, 2) pongamia fruit husk biochar produced at 500°C, 3) Calophyllum fruit husk biochar produced at 500°C, and a control in which neither of the biochar was used. Each treatment were applied with four levels of 4t/ha,8t/ha.12t/ha and 16t/ha biochars. Each treatment was replicated five times and whole experiment set up was done in factorial CRD (Completely randomised design). Two-way ANOVA was also used to analyze the impact of the biochars on soil acidity and other chemical properties. The results showed the application of biochar increased the soil pH in both soils. The increase in pH was more noticeable in acidic soil. In acidic soil calophyllum fruit husk biochar produced at 500 °C applied at 16t/ha showed highest pH at all intervals except at 120 DAI. The increase in pH in neutral soil doesn’t show any particular pattern throughout the incubation period. In acidic soil exchangeable bases such as Ca, Mg, K and Na were highest in red gram straw produced at 400°C. In both acidic and neutral soils, there was no definite trend in micronutrient contents such as extractible Mn, Fe, Zn, and Cu. The incorporation of biochar can cause beneficial changes in soil chemical properties and improve the bioavailability of plant essential nutrients.

Keyword: Biochar, acidic soil, neutral soil, DAI, pH, exchangeable bases, micronutrients.

Introduction

Low soil fertility and limited availability to fertiliser inputs are common issues affecting agricultural production in arid and semi-arid regions of India. Organic and inorganic fertilisers have been used successfully to sustain soil fertility and crop productivity (Widowati *et al.,* 2012). However, the use of organic manures contributes to global warming because of their rapid decomposition and release of greenhouse gases at high temperatures (Palm *et al.,* 2001). Furthermore, the benefits of using organic manures are fleeting and often prohibitively expensive for regular application. The use of recalcitrant organic material such as biochar could be an alternative to enhance soil fertility and improve crop production in such regions. Alternative liming agents with multiple benefits, such as pyrolytic biochars, which improve soil fertility and store carbon in the soil, are gaining popularity (Steiner et al., 2007; Nguyen & Lehmann 2009; Yuan & Xu 2011). Liming has been shown to have a synergistic effect with nutrients applied (via fertilisers) in increasing plant nutrient uptake (Chintala et al., 2012b).

The thermal conversion of biomass (pyrolysis) in a low or no oxygen environment produces high carbonaceous biochar or charcoal with varying properties (Gaskin et al., 2008).Biochars are highly recalcitrant (Lehmann 2007; Rebecca 2007) and can influence soil pH (Xu *et al.,* 2006). It was discovered that applying biochars to acidic soil increases nutrient sorption capacity (Sohi *et al.,* 2010) while decreasing exchangeable acidity (Van Zwieten *et al*., 2009). Several studies have already observed the beneficial effects of biochar on soil quality and fertility parameters. Several incubation and greenhouse studies have demonstrated that biochar application has the potential to improve soil chemical (Atkinson *et al.,* 2010) and physical (Busscher *et al.,* 2010) properties. The use of biochar greatly improved nutrient use efficiency as well as the C content of and had an effect on the chemical properties of the soil as well. Both exchangeable K and soil pH increased in tandem with coffee husk biochar content. The biochar treatment had a much higher efficiency of P fertilisation (De Sousa Lima *et al*., 2018). The highest soil organic carbon, available phosphorus potassium were found significantly higher in the higher doses of the biochars applied (Berihun *et al.,* 2017). However, the effects vary depending on the feedstock, pyrolysis conditions such as temperature and residence time, soil type, and environment (Glaser *et al.,* 2002). So, before applying biochar as a soil amendment technique, it is necessary to analyse its composition and liming potential.

Materials and methods

An incubation study was carried out separately in two different soils ie acidic (pH 5.6) and neutral (pH7.2) to determine the dissolution and release of nutrients from biochar. Three types of biochars such as red gram straw biochar produced at 400 degree celcius ,pongamia fruit husk biochar produced at 500 degree celcius and Calophyllum fruit husk biochar produced at 500 degree celcius .Each biochar were applied at four different levels such as 4t/ha,8t/ha,12t/ha and 16t/ha. One kilogram of various soils was placed in a separate polybag with the graded level of biochar and incubated at field capacity for 150 days. The incubation study was carried out for 150 days until the chemical properties of soil-amendment mixtures reached a steady state.

These soil samples were ground after air-drying, so that they could pass through a 2-mm sieve. The experiment included 12 treatments that were replicated five times in a completely randomised design. Apart from these combination of soil and RDF with neither of the biochar as control were used in the study. The soil and biochar were mixed thoroughly together before being wetted with deionized water to maintain 70% of the soil's field water holding capacity (Naeth *et al.,* 1991).Destructive soil sampling was performed at 30, 60, 90, 120, and 150 days after incubation. The samples were analyzed for pH, primary nutrients (phosphorus and potassium) exchangeable bases (calcium, magnesium and sodium) micronutrient cations (zinc, iron, manganese and copper) by adopting standard procedures. pH was measured using pH meter in soil water suspension of 1:2.5 (Jackson 1973). Available phosphorus were detected by using Brays and Krutz (1945) for acidic soil and Watanabe and Olsen (1965) for neutral soil. Available potassium was analysed by extraction of soil with 1 N (pH 7) ammonium acetate and estimated using flame photometer (Jackson 1973). Available Calcium, Magnesium and micronutrients were analysed using extraction of soil with DTPA and micronutrients were quantified by using ICP-OES (Charles and Fredeen 1997). A two-way analysis of variance was done for each incubation time interval to understand the statistical significance between treatments in each soil.

Result and discussion

Biochar addition increases the pH of both acidic and neutral soils under the study across the incubation period (Table 1). The findings of this study corroborate the findings of previous studies (Chan *et al.,* 2007; Liard *et al.,* 2010b; Yamato *et al.,* 2006) that showed that adding different types of biochar to soil increased soil pH. The increase in pH was more noticeable in acidic soil. Biochar has been shown to improve the pH of acidic, base-poor soils (Chintala *et al.,* 2014 and Anteneh *et al.,* 2014). The release of alkaline chemicals that neutralised soil acidity increased soil pH, which can be attributed to the observed increase in pH of biochar-treated soil. Cations in the feedstock (primarily K, Ca, Si, and Mg) generated metal oxides during pyrolysis, which when applied to soil can react with H^+ and monomeric Al species to alleviate soil pH. Biochar can replace the monomeric Al species from the soil exchange complex in acidic soil because it contains a considerable amount of Ca.

Table 1. Effect of different sources and levels of biochar application on soil pH in acidic and neutral soil at different intervals

Treatments	Acidic soil					Neutral Soil				
	30DAI	60DAI	90DAI	120DAI	150DAI	30DAI	60DAI	90DAI	120DAI	150DAI
Control	5.70	5.71	5.74	5.71	5.78	7.17	7.22	7.27	7.25	7.27
RGBC @ 4 t ha^{-1}	5.72	5.78	5.82	5.88	6.01	7.24	7.35	7.53	7.50	7.60
RGBC @ 8 t ha^{-1}	5.77	5.80	5.83	5.88	6.04	7.28	7.40	7.30	7.30	7.46
RGBC @ 12 t ha^{-1}	5.79	5.81	5.84	5.92	6.06	7.33	7.45	7.41	7.39	7.44
RGBC @ 16 t ha^{-1}	5.82	5.83	5.86	6.02	6.13	7.37	7.47	7.50	7.49	7.51
PFHBC @4 t ha^{-1}	5.83	5.85	5.87	6.04	6.18	7.37	7.33	7.31	7.32	7.40
PFHBC @8 t ha^{-1}	5.86	5.87	5.88	6.08	6.20	7.38	7.39	7.28	7.31	7.44
PFHBC @ 12 t ha^{-1}	5.77	5.77	5.79	5.84	6.03	7.31	7.48	7.38	7.35	7.46
PFHBC @ 16 t ha^{-1}	5.78	5.80	5.83	5.87	6.02	7.34	7.27	7.26	7.30	7.34
CaFHBC @4 t ha^{-1}	5.82	5.85	5.86	5.91	6.05	7.37	7.30	7.25	7.28	7.38
CaFHBC @8 t ha^{-1}	5.90	5.91	5.94	6.03	6.14	7.41	7.42	7.44	7.40	7.44
CaFHBC @ 12 t ha^{-1}	5.89	5.94	5.96	6.04	6.24	7.43	7.45	7.46	7.41	7.47
CaFHBC @ 16 t ha^{-1}	5.93	5.96	5.98	6.03	6.29	7.44	7.46	7.38	7.38	7.47
SE.m	0.02	0.01	0.01	0.02	0.03	0.02	0.01	0.01	0.01	0.01
C.D @0.05	0.08	0.04	0.03	0.07	0.09	0.07	0.03	0.02	0.02	0.04

As a result of the depletion of easily hydrolyzable monomeric Al and the formation of more neutral [Al (OH)3] species, the pH of the soil solution may rise (Novak *et al.*, 2009). Different sources of biochar significantly influenced the soil pH of acidic as well as neutral soil. Increase in the pH of acidic soil showed a definite pattern where calophyllum fruit husk biochar produced at 500 °C had highest pH throughout the incubation period. While in neutral soil, highest pH was observed in calophyllum fruit husk biochar produced at 500 °C at 30 DAI. Later phases of the incubation period saw a highest pH in samples treated with red gram straw biochar produced at 400 °C. It was also observed that pH varied with the biochar raw materials .In one of the study the researchers showed that pine chip biochar has fewer base cations than pea shell biochar, hence it has lower pH reactions (Gaskin *et al.*, 2010). Among the levels of biochar used in the study, significant variation on pH was observed at 60, 90 and 120 DAI in acidic soil and 30 to 120 DAI in neutral soil. In acidic soil, at 60 DAI, highest pH was found in samples applied with 16t/ha (5.87) which are on par with 8t/ha (5.86). At 90 DAI, both 8t/ha and 16t/ha showed highest pH of 5.89. At 120 DAI, highest pH was found in soils applied with 8t/ha (6.00).

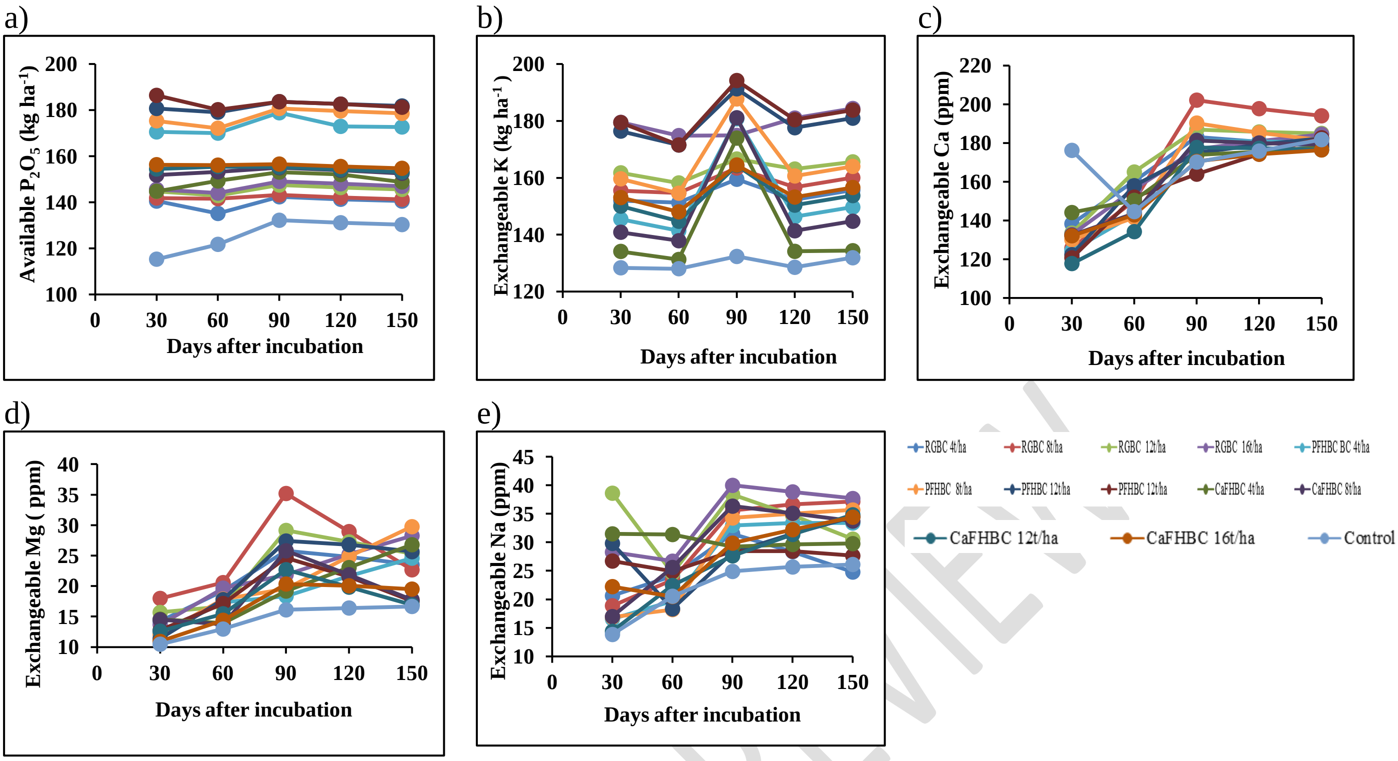


Fig1. Effect of different sources and doses of biochar on the uptake of various nutrients a) Available P_2O_5 b) Exchangeable K c) Exchangeable Ca d) Exchangeable Mg e) Exchangeable Na in acidic soil over the incubation period.

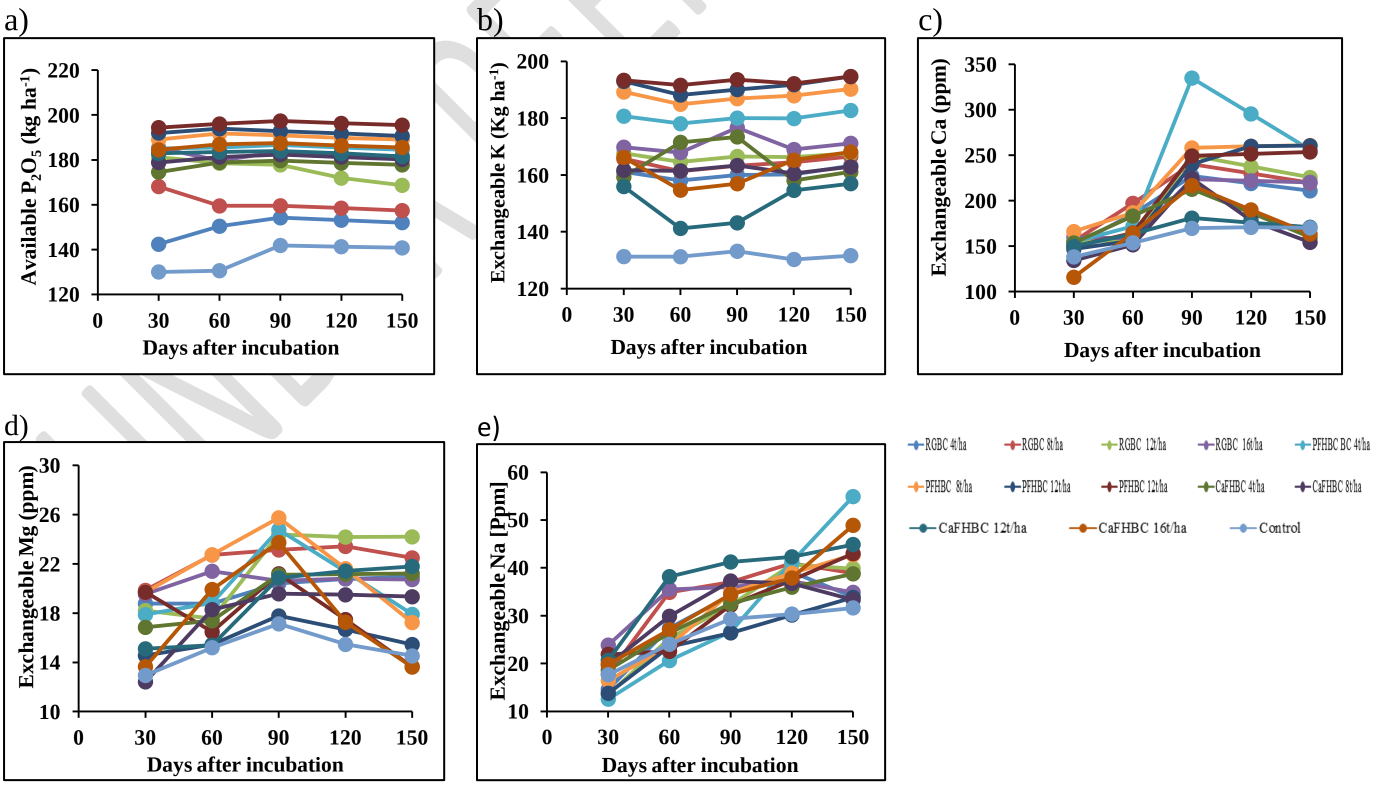


Fig 2: Effect of different sources and doses of biochar on the uptake of various nutrients a) Available P_2O_5 b) Exchangeable K c) Exchangeable Ca d) Exchangeable Mg e) Exchangeable Na in neutral soil.

Enhanced application rate increased the addition of bases, resulting in a higher pH in the current study. These basic cations can be exchanged with the exchangeable Al3+ and H + on the soil exchange complex, resulting in a reduction in exchangeable acidity in both acidic and neutral soils. A decrease in exchangeable Al3+ with increased amounts of Eucalyptus biochar application, and with 0 to 12 t ha-1 of biochar, exchangeable acidity was reduced from 0.60 to 0.39 cmol (p+) kg^{-1}(Anteneh *et al.,*2014). The interactive effect shows a significant influence on soil pH at all intervals in both the soils. In acidic soil calophyllum fruit husk biochar produced at 500 °C applied at 16t/ha showed highest pH at 30,60,90 and 150 DAI with values 5.94,5.96,5.98 and 6.30 respectively. The increase in pH in neutral soil doesn't show any particular pattern throughout the incubation period.

Biochar treatment improved accessible P_2O_5 content in all soils investigated, regardless of type or level at all intervals (Fig 1a). The existence of soluble and exchangeable phosphate in biochar is one probable explanation for increased P availability with biochar application in soil. Such increase in available P_2O_5 content with biochar addition was also reported by Laird *et al.,* (2010); Novak *et al.,* (2009); Parvage *et al.,* (2013) and Hass *et al.,* (2012). Among the sources of biochar used in the study, highest available P_2O_5 was observed in pongamia fruit husk biochar produced at 500 °C and least in red gram straw biochar produced at 400 °C at all intervals in both soils. Among the levels of biochar highest available P_2O_5 was recorded in soils treated with16t/ha at all intervals in acidic soil. Phosphorus is largely present in the ash fraction, where pH-dependent processes and in presence of chelating chemicals regulate its solubilisation (De Luca *et al.,* 2009). Interactive effect in acidic soil showed a significant influence on the available P_2O_5 at 30 DAI only. In neutral soil, highest available P_2O_5 was noticed in 16t/ha at all intervals. The interaction effect of sources and levels of biochar showed a significant influence on the available P_2O_5 at all intervals. Highest available P_2O_5 was noticed in pongamia fruit husk biochar produced at 500 °C at 16t/ha at all intervals. The available P_2O_5 at 30, 60, 90,120 and 150 DAI were noted as 194.41, 196.07, 197.36, 196.29 195.48 kg/ha respectively. In both acidic and neutral soils, there was an overall reduction in P_2O_5 content with time (Fig 1a & 2a). Over time, the combination of P_2O_5 adsorption and precipitation with Fe3+, Al3+, and Ca2+ lowered the amount of accessible P2O5. These findings were comparable to those of Sample *et al.,* (1980) and Sharpley *et al.,* (1983).

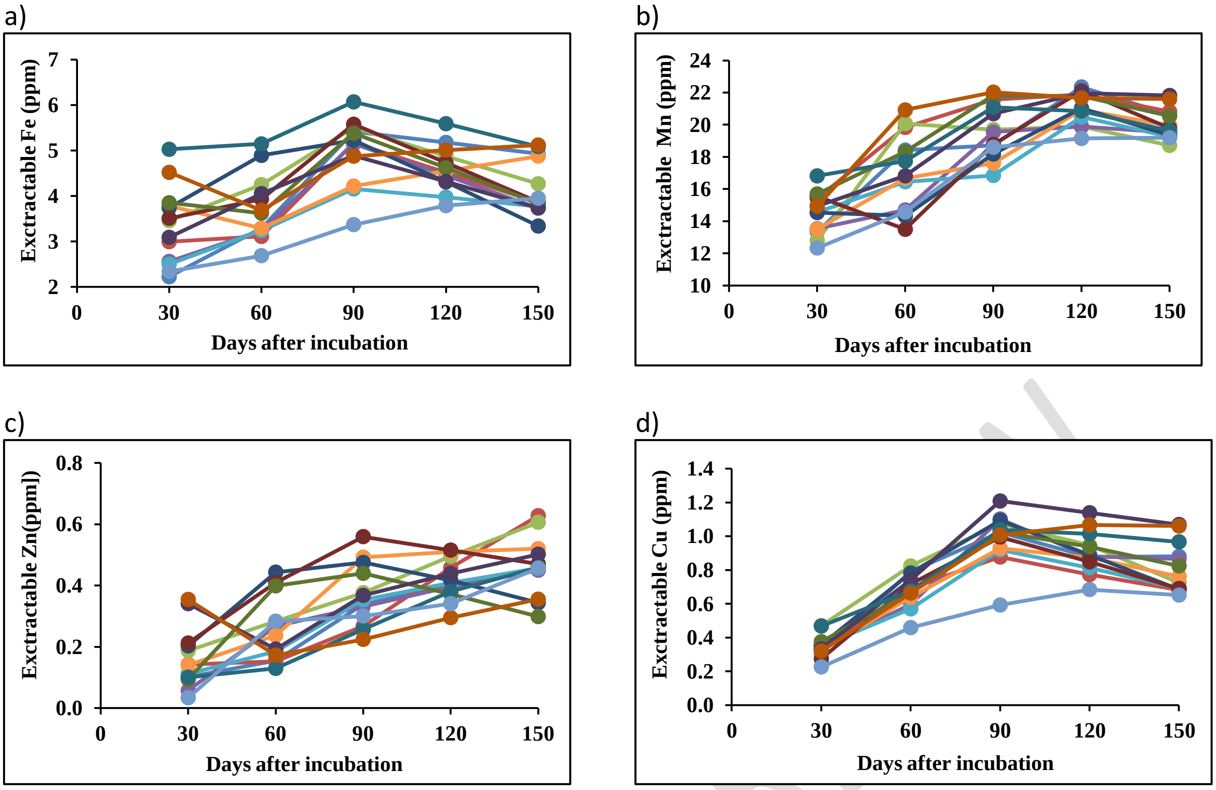


Fig3.Effect of different sources and doses of biochar on the uptake of various nutrients a) Extractable Fe b) Extractable Mn c) Extractable Zn d) Extractable Cu in acidic soil over the incubation period

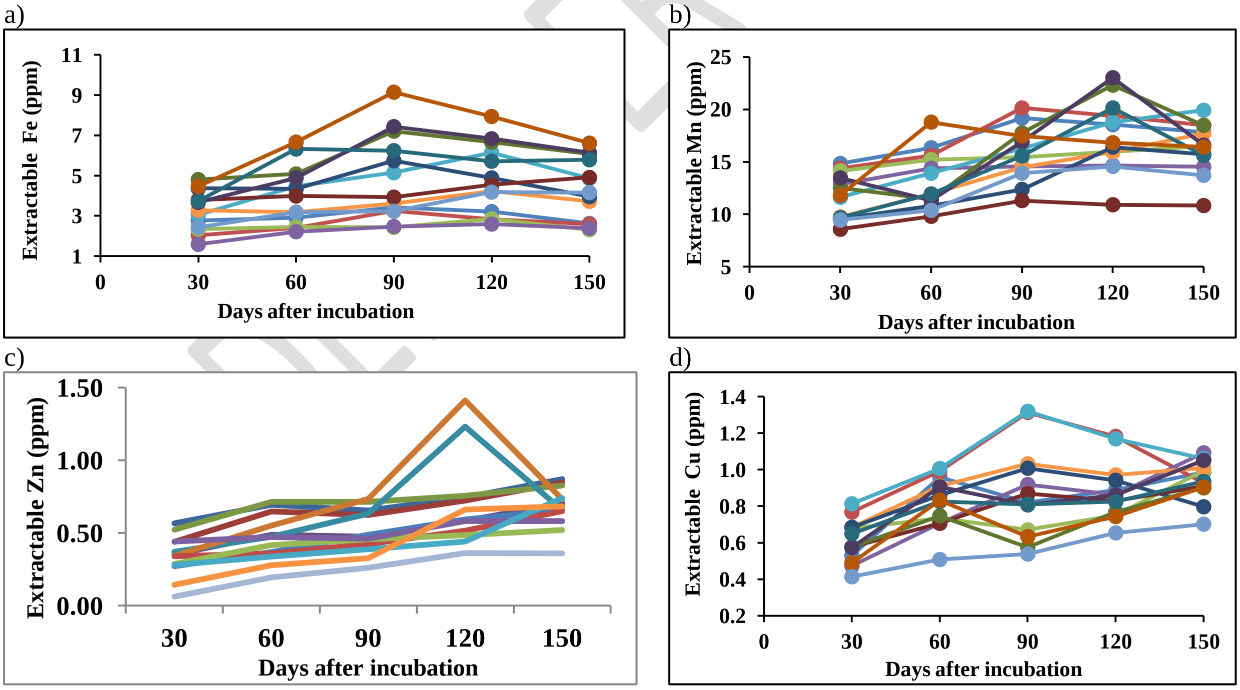
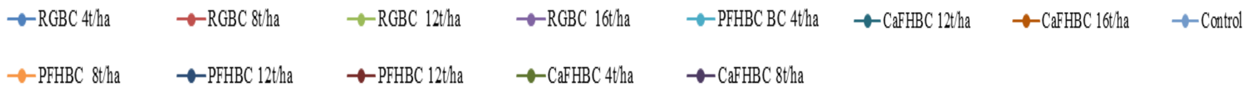


Fig 4:.Effect of different sources and doses of biochar on the uptake of various nutrients a) Extractable Fe b) Extractable Mn c) Extractable Zn d) Extractable Cu in neutral soil over the incubation period



Exchangeable bases such as Ca, Mg, K, and Na varied significantly depending on the type and amount of biochar use (Fig 1& 2). In acidic soil exchangeable bases such as Ca, Mg and Na were highest in red gram straw produced at 400°C. A pattern of increase in exchangeable K content from 30 DAI to 150 DAI was observed being highest in red gram straw produced at 400°C on par with pongamia fruit husk biochar pyrolysed at 500°C. The release of basic cations from biochar causes an increase in exchangeable bases in soil at different periods. Biochar's ash rapidly releases free bases including Ca, Mg, and K into the soil solution, raising not just soil pH but also exchangeable bases. Such observations were also noticed by Lehmann *et al.*, (2003) and Chan *et al.*, (2008). Ca and Mg release was pH dependant and followed a zero order response and a quick release of K that was not pH dependent and followed a zero-order response (Silber *et al.*, 2010).This was observed in the present investigation where in all of the soils examined, exchangeable K increased significantly with the addition of biochar at all application rates (Fig 1b& 2b). We also noticed varying effect of biochar application on exchangeable Ca and Mg in different soils which can be explained by the pH impact. Among the various levels of biochar studied 16t/ha biochar application showed a highest amount of exchangeable K content at all intervals. The highest amount of exchangeable K was given as 170.67, 164.82, 171.57 and 173.93 Kg/ha at 30, 60, 120 and 150 DAI respectively. At all the given intervals, samples treated with the lowest dose of 4t/ha showed least exchangeable K.

With the application of different types and quantities of biochar during a period of incubation in both acidic and neutral soils, there was no definite trend in micronutrient contents such as extractible Mn, Fe, Zn, and Cu (Fig 3& 4). Biochars may cause micronutrient immobilisation in soil due to its high surface area, high metal affinity, increased nutrient retention capacity, presence of acidic and basic functional groups, and propensity to alkalize soil. Such of these mechanisms of metal immobilization due to biochar application were also reported by Park et al. (2011), Vithanage et al. (2014), Cao et al. (2009), Novak et al. (2009) and Paz- Ferreiro et al. (2014). Although there was an increase in Cu content with biochar application, no clear pattern was found in the current study with regard to application rate. The use of biochar may have increased the amount of soluble organic carbon in the soil, allowing Cu to be mobilised. Organic carbon significantly chelates Cu, making it less susceptible to adsorption. Cu concentration is also affected by soluble C and pH, according to Beesley and Marmiroli (2011).

Conclusion

The biochars used in this study were red gram straw biochar produced at 400°C, pongamia fruit husk biochar produced at 500°C, and Calophyllum fruit husk biochar produced at 500°C. With batches of production using different feedstocks and pyrolytic conditions, the properties and reactivity of biochars with soil are highly heterogeneous. In conclusion, this incubation study demonstrated the efficacy of biochars in soil amelioration by increasing soil pH and soil nutrients. The release of basic cations from biochar causes an increase in exchangeable bases in soil at different periods. Biochar's alkalinity, proton consumption capacity (or acid neutralisation capacity), and base cation concentration all contribute to its liming potential. The incorporation of these highly biochar materials can result in beneficial changes in soil chemical properties as well as increased bioavailability of plant essential nutrients. This type of research in different locations using different feedstocks and pyrolytic processes will aid in the development of biochar materials as liming amendments for farmers to reclaim acidic soils with specific recommendations.

References

ANTENEH, A., YITAFERU, B., YIHENEW, G. S. AND AMAR, T., 2014, The Role of biochar on acid soil reclamation and yield of Teff (Eragrostis tef [Zucc] Trotter) in Northwestern Ethiopia. Ethiopia J. Agric. Sci., 6(1): 126-138.

ATKINSON, C.J., FITZGERALD, J.D. AND HIPPS, N.A., 2010. Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review. *Plant and soil*, *337*(1), pp.1-18.

BEESLEY, L. AND MARMIROLI, M., 2011, The immobilisation and retention of soluble arsenic, cadmium and zinc by biochar. Environmental pollution, 159(2): 474-480

BERIHUN, T., TADELE, M. AND KEBEDE, F., 2017, The application of biochar on soil acidity and other physico-chemical properties of soils in southern Ethiopia. Journal of plant nutrition and soil Science, 180(3): 381-388.

BRAY, R.H. AND KURTZ, L.T., 1945. Determination of total, organic, and available forms of phosphorus in soils. Soil science, 59(1): 39-46.

BUSSCHER, W.J., NOVAK, J.M., EVANS, D.E., WATTS, D.W., NIANDOU, M.A.S. AND AHMEDNA, M., 2010. Influence of pecan biochar on physical properties of a Norfolk loamy sand. *Soil Science*, *175*(1), pp.10-14.

CAO, X. D., MA, L. N., GAO, B. AND HARRIS, W., 2009, Dairy-manure derived biochar effectively sorbs lead and atrazine. Environ. Sci. Technol., 43: 3285-3291.

CHAN, K. Y., DORAHY, C. AND TYLER, S., 2007, Determining the agronomic value of composts produced from green waste from metropolitan areas of New South Wales, Australia. Australian Journal of Experimental Agriculture, 47: 1377-1382.

CHAN, K. Y., VAN ZWIETEN, L., MESZAROS, I. A., DOWNIE, C. AND JOSEPH, S., 2008, Using poultry litter biochar as soil amendments. Aust. J. Soil Res., 46: 437-444.

CHARLES, B. AND FREDEEN, K.J., 1997. Concepts, instrumentation and techniques in inductively coupled plasma optical emission spectrometry. *Perkin Elmer Corporation*, *3*, p.2.

CHINTALA, R., JAVIER, M., THOMAS, E. S. AND DOUGLAS, D. M., 2014, Effect of biochar on chemical properties of acidic soil. Arch. Agron. Soil Sci., 60(3): 393-404.

DE LUCA, T. H., MACKENZIE, M. D. AND M. J., 2009, Biochar effects on soil nutrient transformations. In: Lehmann J, Joseph S (Eds) Biochar for environmental management science and technology. Earthscan, London, 72- 87.

DE SOUSA LIMA, J. R., DE MORAES SILVA, W., DE MEDEIROS, E. V., DUDA, G. P., CORRÊA, M. M., MARTINS FILHO, A. P., CLERMONT-DAUPHIN, C., ANTONINO, A. C. D. AND HAMMECKER, C., 2018, Effect of biochar on physicochemical properties of a sandy soil and maize growth in a greenhouse experiment. Geoderma, 319: 14-23.

GASKIN, J. W., SPEIR, R. A., HARRIS, K., DAS, K. C., LEE, R. D., MORRIS, L. A. AND FISHER, D. S., 2010, Effect of peanut hull and pine chip biochar on soil nutrients, corn nutrient status, and yield. Agron., 102: 623-633.

GASKIN, J.W., STEINER, C., HARRIS, K., DAS, K.C. AND BIBENS, B., 2008. Effect of low-temperature pyrolysis conditions on biochar for agricultural use. *Transactions of the ASABE*, *51*(6), pp.2061-2069.

GLASER, B., LEHMANN, J. AND ZECH, W., 2002. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal–a review. *Biology and fertility of soils*, *35*(4), pp.219-230.

HASS, A., JAVIER, M. G., ISABEL M. L., HARRY, W. G., JONATHAN J. H. AND DOUGLAS G. B., 2012, Chicken manure biochar as liming and nutrient source for acid Appalachian. Soil. J. Environ. Qual., 41(4): 1096-1106

JACKSON, M.L., 1973, Soil chemical analysis, pentice hall of India Pvt. Ltd., New Delhi, India, 498, pp.151-154.

LAIRD, D. A., FLEMING, P., DAVIS, D. D., ROBERT, H., WANG, B. AND KARLEN, D. L., 2010a, Biochar impact on nutrient leaching from a Midwestern agricultural soil. Geoderma, 158: 436-442.

LEHMANN J. 2007. Bio-energy in the black. Front Ecol Environ. 5:381–387.

LEHMANN, J., DA SILVA J. R. J. P., STEINER, C., NEHLS, T., ZECH, W. AND GLASER, B., 2003, Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. Plant Soil, 249: 343-357.

NAETH, M.A., BAILEY, A.W., PLUTH, D.J., CHANASYK, D. AND HARDIN, R.T., 1991. Grazing impacts on litter and soil organic matter in mixed prairie and fescue grassland ecosystems of Alberta.

NGUYEN, T. H., CHO, H. H., POSTER, D. L. AND BALL, W. P., 2007, Evidence for a pore-filling mechanism in the adsorption of aromatic hydrocarbons to a natural wood char. Environmental science & technology, 41(4): 1212-1217.

NOVAK, J. M., BUSSCHER, W. J., LAIRD, D. L., AHMEDNA, M., WATTS, D. W. AND NIANDOU, M. A. S., 2009, Impact of biochar amendment on fertility of a south-eastern coastal plain soil. Soil Sci., 174: 105-112.

PALM, C.A., GACHENGO, C.N., DELVE, R.J., CADISCH, G. AND GILLER, K.E., 2001. Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database. *Agriculture, ecosystems & environment*, *83*(1-2), pp.27-42.

PARK, J. H., CHOPPALA, G. H., BOLAN, N. S., CHUNG, J. W. AND CHUASAVATHI, T., 2011, Biochar reduces the bioavailability and phytotoxicity of heavy metals. Plant Soil, 348: 439-451.

PARVAGE, M. M., BARBRO, U., ERIKSSON, J., JEFFERY, S. AND HOLGER, K., 2013, Phosphorus availability in soils amended with wheat residue char. Biol. Fert. Soils., 49(2): 245-250.

PAZ-FERREIRO, J., LU, H., FU, S., ME´NDEZ, A. AND GASCO, G., 2014, Use of phytoremediation and biochar to remediate heavy metal polluted soils: a review. Solid Earth, 5: 65-75.

REBECCA R. 2007. Rethinking biochar. Environ Sci Technol. 41:6032–6033

SAMPLE, E. C., SOPER, R. J. AND RACZ, G. J., 1980, Reactions of Phosphate Fertilizers in Soils, The American Society of Agronomy, Madison, Wis, USA.

SHARPLEY, A. N., 1983, Effect of soil properties on the kinetics of phosphorus desorption. Soil. Sci. Soc. Am. J., 47(3): 462-467.

SILBER, A., LEVKOVITCH, I. AND GRABER, E. R., 2010, pH dependent mineral release and surface properties of corn straw biochar: Agronomic implications. Environ. Sci. Technol., 44: 9318-9323.

SOHI SP, KRULL E, LOPEZ-CAPEL E, BOL R. 2010. A review of biochar and its use and function in soil. Adv Agron. 105:47–82.

STEINER, C., TEIXEIRA, W.G., LEHMANN, J., NEHLS, T., DE MACÊDO, J.L.V., BLUM, W.E. AND ZECH, W., 2007. Long term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered Central Amazonian upland soil. *Plant and soil*, *291*(1), pp.275-290.

VAN ZWIETEN, L., SINGH, B., JOSEPH, S., KIMBER, S., COWIE, A. AND CHAN, K.Y., 2012. Biochar and emissions of non-CO2 greenhouse gases from soil. In *Biochar for environmental management* (pp. 259-282). Routledge.

VITHANAGE, M., RAJAPAKSHA, A. U., ZHANG, M., THIELE-BRUHN, S., LEE, S. S. AND OK, Y. S., 2014, Acid-activated biochar increased sulfamethazine retention in soils. Environ. Sci. Pollut. Res., 22(3): 1-12.

WIDOWATI, W.H., GURITNO, B. AND SOEHONO, L.A., 2012. The effect of biochar on the growth and N fertilizer requirement of maize (Zea mays L.) in green house experiment. *Journal of Agricultural Science*.

XU, J.M., TANG, C. AND CHEN, Z.L., 2006. The role of plant residues in pH change of acid soils differing in initial pH. *Soil Biology and Biochemistry*, *38*(4), pp.709-719.

YAMATO, M., OKIMORI, Y., WIBOWO, I. F., ANSHIORI, S. AND OGAWA, M., 2006, Effects of the application of charred bark of acacia mangium on the yield of maize, cowpea and peanut, and soil chemical properties in south Sumatra, Indonesia. Soil. Sci. Plant. Nutr., 52: 489-495.

YUAN, J. H. AND XU, R. K., 2011, The amelioration effects of low temperature biochar generated from nine crop residues on an acidic ultisol. Soil Use and Management, 27(1): 110-115.