INVESTIGATIONS ON THE EFFICACY OF BIOCHAR FROM TENDER COCONUT HUSK FOR ENHANCED CROP PRODUCTION

by

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(2011-21-115)

THESIS

Submitted in partial fulfillment of the

requirements for the degree of

DOCTOR OF PHILOSOPHY IN AGRICULTURE

Faculty of Agriculture

Kerala Agricultural University

DEPARTMENT OF SOIL SCIENCE AND AGRICULTURAL CHEMISTRY

COLLEGE OF AGRICULTURE

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KERALA, INDIA

2015

DECLARATION

I, hereby declare that this thesis entitled **"Investigations on the efficacy of biochar from tender coconut husk for enhanced crop production"** is a bonafide record of research done by me during the course of research and that the thesis has not previously formed the basis for the award of any degree, diploma, fellowship or other similar title, of any other University or Society.

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CERTIFICATE

Certified that this thesis entitled "**Investigations on the efficacy of biochar from tender coconut husk for enhanced crop production**" is a record of research work done independently by **Ms. Mariya Dainy M. S. (2011-21-115)** under my guidance and supervision and that has not previously formed the basis for the award of any degree, diploma, fellowship or associateship to her.

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AKNOWLEDGEMENT

I bow my head before God Almighty for all the bountiful blessings he has showered on me at each and every moment without which this study would never have seen light.

Let me place on record my profound feeling of gratitude and sincere thanks to my chair person of the advisory committee, Dr. P. B. Usha, Professor, Department of Soil Science and Agricultural Chemistry for her note worthy guidance, creative suggestions and sustained interest. I am indebted to my major advisor for her constant encouragement, timely advice and motherly approach during the course of study as well as investigation and in the execution of this thesis. This work would not have been possible without her valuable help and support.

I would express my sincere gratitude to Dr. N. Saifudeen, former Professor and Head, Department of Soil Science and Agricultural Chemistry, for his continuous and timely advice, constructive criticisms and guidance at all the stage of research work.

My heartfelt thanks to Dr. Sumam Susan Varghese, Professor and Head, Department of Soil Science and Agricultural Chemistry, for her keen interest, immense help, constructive suggestions, timely support and co-operation rendered throughout the course of this research endeavor.

I am grateful to Dr. K. C. Manorama Thampatti, Professor, Department of Soil Science and Agricultural Chemistry for her valuable suggestions, timely support and critical evaluation during the course of this work.

I express my sincere gratitude to Dr. Shehana R.S., Professor for her valuable suggestions, ever willing help and support which had been rendered whole heartedly throughout my research work.

I am thankful to Dr. V. A. Celine, Professor & Head, Dept of Olericulture, for her guidance and suggestions rendered to me in formulating the thesis.

I wish to express my heartfelt thanks to Dean, College of Agriculture, Vellayani for providing me all the necessary facilities from the University during the whole course of study.

I express my gratitude towards Dr. C. R. Sudharmai Devi, Professor, Dr. Sumam George, Professor, Dr. Usha Mathew, Professor, Dr. K. Ushakumari, Professo, Professor, Dr. Sam T. Kurumthottikkal, Professor and Dr. Thomas George, Associate Professor, for the utmost help and encouragement during the study period.

I accord my sincere thanks to Mr. C. E. Ajith Kumar, Junior Programmer, Department of Agricultural Extension for helping me in getting the data analysed.

I sincerely thank the facilities rendered by the library of College of Agriculture, Vellayani.

I am thankful to non-teaching staff of the Department of Soil Science and Agricultural Chemistry especially to Minichechi, Mayachechi,, Biju chettan, Anish, Soumya, Shersha, casual labourer Shinichechi and all others for their co-operation during the course of study.

My heartful thanks to my loving friends Asha B. Nair, Poornima K. Das, Mini chechi, Siji, Appu, Vipitha, Bismi, Praveen John, Pintu Roy, Anita chechi, Fazila, Shimi and Aswathy chechi who had always for me as friends, loving support, confidence and moral support so much more. Their care and constant encouragement has gone a long way in helping me to overcome the problems I had to face during the course of my work.

I wish to express my gratefulness to my seniors Jinsychechi, Resmichechi, Lekshmichechi, Naveen sir and Meera chechi for their valuable advice and guidance during the course of my work.

I am grateful to Kerala State Council for Science, Technology and Environment for the Research Fellowship and contingency grant allotted to me during the course of the study.

I am most indebted to my loving father Mr. Sebastian Muttikkal, mother Mrs. Mary Sebastain Muttamthottil, husband Mr. Joseph Bipin, brother Dain Sebastian, father-in-law E. J. Jacob, mother-in-law Telma Jacob, brother-in-law George Praveen, Fr. Jaiju Elenjikkal, Fr. Sebastian Muttamthottil, my cousins Reny, Leny, Sr. Baby, Sr. Kochurani and other cousins and relatives, for their affection, constant encouragement, moral support and blessings that have enabled me to undertake this work without which I would not have complete this research.

Mariya Dainy M. S.

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LIST OF ABREVIATIONS

%	Per cent
µg	Microgram
μm^2	Micro square metre
AMF	Arbuscular Mycorrhizal Fungi
B: C	Benefit: Cost
BC	Biochar
B	Boron
BNF	Biological Nitrogen Fixation
BET	Brunauer Emmett Teller
Ca	Calcium
CD	Critical Difference
CEC	Cation Exchange Capacity
cm	Centimeter
C: N	Carbon: Nitrogen
CO_2	Carbon dioxide
DAP	Di Ammonium Phosphate
DAS	Days After Sowing
dS	Deci Siemens
et al	And others
Fe	Iron
Fig.	Figure
FYM	Farmyard Manure
g	Gram
GHG	Green House Gas
h	Hour
ha^{-1}	Per hectare
K	Potassium

KAU	Kerala Agricultural University
kg	Kilogram
l	Litre
LFA	Lignite Fly Ash
Mg	Magnesium
Mo	Molybdenum
m	Metre
mg	Milligram
min	Minutes
ml	Millilitre
mm	Millimetre
N	Nitrogen
NUE	Nitrogen Use Efficiency
°C	Degree Celsius
P	Phosphorus
PGPR	Plant Growth Promoting Rhizobacteria
RBD	Randomized Block Design
POP	Package of Practices
S	Sulphur
SSA	Specific Surface Area
s	Seconds
t	Tonnes
TDM	Total Dry Matter
Var.	Variety
WHC	Water Holding Capacity
Zn	Zinc

Dedicated to

My

Parents, Husband and Brother

Introduction

1. INTRODUCTION

Food, energy and environmental crises justifiably dominate the headlines in the world today. They are primarily caused by the demand of ever-increasing global population under a high-carbon economic model. Land degradation and climate change are relevant associated processes requiring change in order to solve these crises. For natural resource-abundant developing countries, land degradation and climate change tend to aggravate poverty.

Maintaining an appropriate level of soil organic matter and biological cycling of nutrients is crucial for the success of any soil management in the humid tropics. Cover crops, mulches, compost, or manure additions have been used successfully, supplying nutrients to crop supporting rapid nutrient cycling through microbial biomass, and helping to retain applied mineral fertilisers better. The benefits of such amendments are, however, often short-lived, especially in the tropics, since decomposition rates are high and the added organic matter is usually mineralised to carbon dioxide within only a few cropping seasons (Bol and Kuzyakov, 2000). Organic amendments therefore have to be applied each year to sustain soil productivity. In this context, production of biochar with sustainably managed natural resources can sequester atmospheric carbon and manage soil health.

Biochar is the carbon-rich product obtained by the thermal decomposition of organic material under zero or limited supply of oxygen, and at relatively low temperatures (<700°C) by the process of pyrolysis (Lehmann, 2007). Its primary use is not for fuel, but for biosequestration or atmospheric carbon capture and storage. Biochar is much more persistent in soil than any other form of organic matter and it can remain stable in soil for hundreds to thousands of years that makes it a prime source for carbon sequestration. Because of its aromatic structure dominated by aromatic carbon, biochar has been found to be biochemically recalcitrant compared to uncharred, parent organic matter and have considerable potential to enhance the long term soil carbon pool and a net carbon withdrawal from the atmosphere by twenty per cent. Biochar application can reduce emissions of other green house gases like nitrous oxide by eighty per cent and completely suppresses methane emissions.

Biochar has great importance in improving soil fertility and it can act as a soil amendment to increase crop yield and plant growth by supplying and retaining nutrients than other organic matter such as leaf litter, compost or manure. Because of its porous nature, it has a lot of surface area for water and nutrients to hold on and supply to plants as well as keep carbon intact without releasing to the atmosphere. Biochar application results in better water holding capacity, increased pH, increased cation exchange capacity (Cheng *et al.*, 2006), increased biological nitrogen fixation (BNF), reduces leaching loss of nutrients especially nitrogen into the ground water (Ding *et al.*, 2010) and that of phosphorous into surface waters, reduces bulk density of soil providing a medium for adsorption of plant nutrients and improved conditions for soil micro-organisms and reduces soil degradation. Biochar could adsorb ammonium ion predominantly by cation exchange and it can be used as a nitrification inhibitor.

Animal manure, agricultural residues and municipal yard waste can be a significant burden on the environment. Nutrient contained in manure may cause eutrophication of surface waters or pollute ground water. Land fills of municipal green wastes may generate large quantities of green house gases. Biochar production is an intelligent way of recycling organic wastes and reduces environmental pollution. During biochar production, biofuel and biogas are generated that can be used as bioenergy. The potential to combine bioenergy production, sustainable agriculture and waste management while reducing green house gas emissions into an approach using biochar offers the best way for how to handle biowaste in the future economy.

Kerala, being a land of coconut, has a large area under coconut farming. Twenty per cent of the nuts is used as tender coconut. Tender coconut consumption in India account for 15 per cent of the total production of 15 billion coconuts in India. The consumption pattern in Kerala has revealed that there has been a whopping 130 per cent increase in the sales of tender coconut in Kerala, which is the largest producer with 5799 million nuts. Tender coconut husk, is not suitable for the coir industry and it is a major biowaste which accumulates on the road sides and it is a rich source of nutrients also. The best way to utilize it for crop production without environmental pollution is by converting it to biochar.

Fabricated production units for making biochar from tender coconut husk by the process of pyrolysis are scanty. There is no standardised procedure for the production of biochar from tender coconut husk. The physical and chemical characteristics of biochar from tender coconut husk are unknown. Sorptive and desorptive properties of the produced biochar have also to be determined. When tender coconut husk biochar is applied to soil, its effects on soil properties, crop growth and yield should also be studied.

Vegetables are universally accepted as protective foods and have been well advocated in solving the problems of poverty and malnutrition. They play an important role in human health by providing carbohydrates, proteins, minerals and vitamins. Among the vegetables grown in Kerala, vegetable cowpea or yard long bean (*Vigna unguiculata* subsp. *sesquipedalis*) occupies a prime position owing to its high nutrient content and consumer preference and hence its yield and quality are important.

Taking all these problems into consideration, the present study was undertaken with the following objectives:

1. To produce biochar from tender coconut husk using a fabricated production unit
2. To characterise biochar produced from tender coconut husk for its various physical and chemical properties
3. To study the sorption and desorption of major and micro nutrients using biochar
4. To investigate the efficacy of biochar from tender coconut husk in field using yard long bean as the test crop.

Review of literature

2. REVIEW OF LITERATURE

A research project entitled 'Investigations on the efficacy of biochar from tender coconut husk for enhanced crop production' was carried out at College of Agriculture, Vellayani. The literature pertaining to the characterization of biochar, its effect on sorption and desorption of nutrients, carbon dioxide emission and crop production are described below.

Biochar is an effective adsorbent and it has vast surface area and complex pore structure, which promotes beneficial chemical and microbial interactions. Biochar can improve plant productivity directly as a result of its nutrient content and release characteristics, as well as indirectly by (i) improved retention of nutrients (Lehmann, 2007) especially for phosphorus, calcium, sulfur, and nitrogen (Mann, 2002); and production of neutral pH (Fowles, 2007; Laird, 2008); (ii) improvements in soil pH (Rondon *et al.*, 2007); (iii) increased soil CEC (Liang *et al.*, 2006); (iv) improved soil physical properties (Chan *et al.*, 2007), including an increase in soil water retention (Laird *et al.*, 2010); and alteration of soil microbial populations and functions (Pietikainen *et al.*, 2000).

Higher nutrient availability for plants is the result of both the direct nutrient additions by biochar and greater nutrient retention (Lehmann *et al.*, 2003), but it can also be an effect of changes in soil microbial dynamics. Long-term benefits for nutrient availability include a greater stabilization of organic matter, concurrent slower nutrient release from added organic matter, and better retention of all the cations due to a greater CEC. The formation of functional groups and adsorption sites on surfaces and within pores of biochar could influence its CEC (Cheng *et al.*, 2006; Liang *et al.*, 2006) and, consequently, the capacity of biochar amended soils to form complexes with metal ions. Both CEC and pH are also frequently increased through biochar applications, by up to 40 per cent of initial CEC and by one pH unit, respectively (Topoliantz *et al.*, 2002). Biochar application can reduce nutrient leaching from soil (Ding *et al.*, 2010).

Biochar efficiently adsorbs ammonia according to Oya and Iu (2002) and Iyobe *et al.* (2004) reported that biochar acts as a binder for ammonia in soil, therefore having the potential to decrease ammonia volatilization from soil surfaces. Additions of biochar plus fertilizer (NH_4^+) increased radish yields more than the addition of fertilizer alone, indicating reduced N leaching and increased N use efficiency (Chan *et al.*, 2007).

The incorporation of biochar into soil modifies soil physical properties such as structure, texture, porosity, bulk density, and particle size distribution. Incorporation of biochar may therefore increase the soil volume and reduce the bulk density of the soil. Biochar has been shown to improve the water retention in sandy soils (Brockhoff *et al.*, 2010).

Application of biochar to soil can substantially improve the productivity of crops such as maize, soybean, radish, sorghum, potato, wheat, pea, oats, rice, and cowpea (Lehmann *et al.*, 2003). Rondon *et al.* (2007) reported that the beans (*Phaseolus vulgaris* L.) showed positive yield effects on biochar application rates up to 50 t C ha^{-1}. Biochar is a stable form of C and it will remain in the soil for hundreds to thousands of years (DeLuca *et al.*, 2006; Lehmann, 2007). Processing biomass into biochar can stabilize organic C and thus reduce CO_2 emissions (Lehmann *et al.*, 2006). This chapter gives a brief review of the work done on biochar in different crops.

2. 1. CHARACTERIZATION OF BIOCHAR

Verheijen (2009) characterized electro-chemical properties of biochar and summarized that pH, C, N, C: N ratio, P and K were 8.10, 543.00 g kg^{-1}, 22.30 g kg^{-1}, 61, 23.70 g kg^{-1} and 24.30 g kg^{-1} respectively.

Zheng *et al.* (2010) evaluated the physico-chemical properties of biochars prepared under different conditions from selected feed stocks and found out that corn cob biochar prepared at 300°C had specific surface area (SSA), C, H and N content of 2.42 m^2 g^{-1}, 70.54 per cent, 4.19 per cent, 0.81 per cent respectively, at 350° C, biochar recorded SSA of 3.36 m^2 g^{-1}, C content of 72.92 per cent, H content of 3.79 per cent and N content of 0.79 per cent and that produced at 400°C had SSA of 4.70 $m^2 g^{-1}$, C content of 75.23 per cent, H content of 3.37 per cent and N content of 0.82 per cent. Biochar produced at 450°C had SSA, C, H and N content of 7.79 $m^2 g^{-1}$, 77.84 per cent, 2.95 per cent, 0.86 per cent respectively and that produced at 500°C had SSA, C, H and N content of 17.08 $m^2 g^{-1}$, 80.85 per cent, 2.5 per cent, 0.97 per cent respectively. At 550°C, biochar produced had SSA, C, H and N content of 30.57 $m^2 g^{-1}$, 82.62 per cent, 2.25 per cent, 0.84 per cent respectively.

Major *et al.* (2010a) produced and characterized wood biochar to evaluate its effect on maize yield and nutrition during 4 years to a Colombian savanna oxisol and reported that pH, CEC, C: N ratio, H: C ratio, O: C ratio, ash content, total C, N, P, K, Ca and Mg contents in the produced biochar were 9.20, 11.19 cmol (+) kg^{-1}, 120.00, 0.018, 0.260, 4.60 per cent, 72.90 per cent, 0.760 per cent, 29.80 $\mu g\ g^{-1}$, 463.80 $\mu g\ g^{-1}$, 330.70 $\mu g\ g^{-1}$, 48.9 $\mu g\ g^{-1}$ respectively.

Islami *et al.* (2011) investigated the characteristics of biochar made from FYM and cassava stem and reported that pH, C, N, P, K and CEC were 7.90, 255.50 g kg^{-1}, 7.80 g kg^{-1}, 8.50 g kg^{-1}, 7.90 g kg^{-1}, 17.70 cmol (+) kg^{-1} respectively for FYM biochar and 8.10, 404.20 g kg^{-1}, 0.90 g kg^{-1}, 2.10 g kg^{-1}, 9.40 g kg^{-1} and 12.50 cmol (+) kg^{-1} respectively for cassava stem biochar.

Sukartono *et al.* (2011) characterized biochars produced from cattle dung and coconut shell, produced using simple stove made of brick (200 to 330°C) and autothermal-combusting of feedstock's in pit (temperature was fluctuated in between 190 and 280°C) and reported that cattle dung biochar had pH of 8.90, EC of 1.77 dS m^{-1}, CEC of 16.79 cmol (+) kg^{-1} and bulk density of 0.670 g cm^{-3}. C, N, P, K, Ca and Mg contents were 23.53 per cent, 0.730 per cent, 0.570 per cent, 0.69 per cent, 0.510 per cent and 0.440 per cent respectively. Biochar from coconut shell recorded pH of 9.90, EC of 1.75, CEC of 11.78 cmol (+) kg^{-1} and bulk density of 0.710 g cm^{-3}. C, N, P, K, Ca and Mg contents of coconut shell biochar were 80.59 per cent, 0.340 per cent, 0.100 per cent, 0.840 per cent, 0.04 per cent and 0.06 per cent respectively.

Saranya *et al.* (2011) studied the characteristics of biochar to investigate its potential as an alternate carrier to lignite for the preparation of biofertilizers in India and reported that WHC, moisture, bulk density, porosity, total surface area, pH, total C, total H, total O and total N were 200 per cent, 20 to 30 per cent, 1.62 g cm^{-3}, 73.33 per cent, 870.90 m^2 g^{-1}, 7, 84 per cent, 2.30 per cent, 10.70 per cent, 0.01 per cent and 3.24 per cent respectively for acacia wood based biochar and 430 per cent, 12 per cent, 1.22 g cm^{-3}, 82.27 per cent, 926.54 m^2 g^{-1}, 6.56, 86 per cent, 2.20 per cent, 10.22 per cent, 0.942 per cent and 3.00 per cent respectively for coconut shell based biochar.

Rojith and Singh (2012) characterized biochar, produced by slow pyrolysis of coir pith at 500^{0}C and reported that pH, C, H, N and S were 6.50, 62.24 per cent, 4.82 per cent, 0.27 per cent and 0.13 per cent respectively. When it was produced at 600°C, coir pith biochar recorded pH of 7.40, C content of 63.14 per cent, H content of 3.62 per cent, N content of 0.64 per cent and S content of 0.21 per cent.

Wu *et al.* (2012) investigated the properties of rice straw-derived biochar, produced at different temperatures (300, 400, 500, 600 and 700^{0}C) and reported that the biochar produced at 400^{0}C had C content of 77.20 per cent, N content of 1.74 per cent and ash content of 28.30 per cent.

Shenbagavalli and Mahimairaja (2012) characterized biochar produced from different biological wastes, in a specially designed pyrolysis-stove and reported that paddy straw biochar had pH of 9.68, EC of 2.41dS m^{-1}, CEC of 8.20 cmol (+) kg^{-1}, total organic C content of 540.00 g kg^{-1}, total N content of 10.50 g kg^{-1}, C:N ratio of 51.50, P content of 1.20 g kg^{-1}, K content of 2.40 g kg^{-1}, Ca content of 4.50 g kg^{-1} and Mg content of 6.20 g kg^{-1}. Coconut shell biochar had pH of 9.18, EC of 0.730 dS m^{-1}, CEC of 12.50 cmol (+) kg^{-1}, total organic C content of 910.00 g kg^{-1}, total N content of 9.40 g kg^{-1}, C: N ratio of 96.80, P content of 3.20 g kg^{-1}, K content of 10.40 g kg^{-1}, Ca content of 8.50 g kg^{-1} and Mg content of 5.80 g kg^{-1}. Groundnut shell biochar had pH of 9.30, EC of 0.390 dS m^{-1}, CEC of 5.40 cmol (+) kg^{-1}, total organic C content of 770.00 g kg^{-1}, total N content of 11.00 g kg^{-1}, C: N ratio of 70.00, P content of 0.600 g kg^{-1}, K content of

6.20 g kg^{-1}, Ca content of 3.20 g kg^{-1} and Mg content of 2.10 g kg^{-1}. Coir waste biochar had pH of 9.30, EC of 0.39 dS m^{-1}, CEC of 3.20 cmol (+) kg^{-1}, total organic C content of 760.00 g kg^{-1}, N content of 8.50 g kg^{-1}, C: N ratio of 89.40, P content of 1.50 g kg^{-1}, K content of 5.30 g kg^{-1}, Ca content of 1.80 g kg^{-1} and Mg content of 1.40 g kg^{-1}.

Jien and Wang (2013) characterized biochar made from wood, to study its effects on soil properties and erosion potential in a highly weathered soil and reported that pH, TOC, total N, C:N ratio, CEC, Exchangeable Ca, Mg, Na, K and SSA were 9.94, 78.30 per cent, 0.64 per cent, 121.00, 22.30 cmol (+) kg^{-1}, 8.84 cmol (+) kg^{-1}, 0.41 cmol (+) kg^{-1}, 0.19 cmol (+) kg^{-1}, 0.27 cmol (+) kg^{-1} and 340 m^2 g^{-1}.

In order to evaluate the effect of four different biochar additions on the emission of the greenhouse gases CO_2 and N_2O, Ameloot *et al.* (2013) produced and characterized biochar from digestate, a waste-product of the wet fermentation of swine manure, and willow wood by pyrolyzing the digestate at 350^{0}C and 700 ^{0}C, yielding four biochar types. Biochar type DS350 had C content of 39.70 per cent, N content of 2.15 per cent, C: N ratio of 18.40, moisture content of 4.23 per cent and ash content of 2.48 per cent with 29.19 per cent volatile matter. pH, surface area, pore size and pore volume of this biochar type were 10.10, 1.32 m^2 g^{-1}, 3.89 nm and 4.35 mm^{3}g^{-1} respectively. Biochar type DS700 had C content of 34.50 per cent, N content of 1.03 per cent, C:N ratio of 34.5, moisture content of 3.04 per cent, ash content of 2.75 per cent, volatile matter of 10.37 per cent, pH of 11.60, surface area of 9.02 m^2 g^{-1}, average pore size of 6.74 nm and pore volume 15.66 mm^3 g^{-1}.

Wiedner *et al.* (2013) performed the chemical evaluation of chars produced by thermo-chemical conversion (gasification, pyrolysis and hydrothermal carbonization) of agro-industrial biomass on a commercial scale and reported that biochar from poplar had pH of 9.96, EC of 997.00 mS cm^{-1}, ash content of 178.00 g kg^{-1}, C content of 701.00 g kg^{-1}, N content of 14.90 g kg^{-1} with C: N ratio of 47.00. Wheat biochar recorded pH of 9.70, EC of 1327.00 mS cm^{-1}, ash content of 329 g kg^{-1}, C content of 575.00 g kg^{-1}, N content of 7.80 g kg^{-1} with C: N ratio of 73.70. Biochar from wood chips had pH of 9.70, EC of 1327.00 mS cm^{-1}, ash content of 329.00 g kg^{-1}, C content of 575.00 g kg^{-1}, N content of 7.80 g kg^{-1} with C: N ratio of 73.70 and that produced from miscanthus recorded pH of 9.99, EC of 13024.00 mS cm^{-1}, ash content of 154.00 g kg^{-1}, C content of 712.00 g kg^{-1} and N content of 1.30 g kg^{-1}.

Lee *et al.* (2013) conducted an experiment to compare the properties of biochar from biomass residues produced by slow pyrolysis at 500 ^{0}C. Biochar made from sugarcane bagasse had moisture content of 1.30 per cent, volatile matter content of 9.17 per cent, fixed C of 80.97 per cent, ash content of 8.57 per cent, pH of 9.30, C content of 85.59 per cent, N content of 1.11 per cent, P content of 504.00 mg kg^{-1}, K content of 2643.00 mg kg^{-1}, Ca content of 1798.00 mg kg^{-1}, Mg content of 390.00 mg kg^{-1}, Fe content of 1276.00 mg kg^{-1} and Mn content of 104.00 mg kg^{-1}where as that produced from coco- peat exhibited moisture content of 2.55 per cent, volatile matter content of 14.30 per cent, fixed C of 84.44 per cent, ash content of 15.90 per cent, pH of 10.30, C content of 84.44 per cent, N content of 1.02 per cent, P content of 302.00 mg kg^{-1}, K content of 22,960.00 mg kg^{-1}, Ca content of 2667.00 mg kg^{-1}, Mg content of 544.00 mg kg^{-1}, Fe content of 2088.00 mg kg^{-1} and Mn content of 33.00 mg kg^{-1}. Paddy straw biochar produced was having properties like moisture content of 2.07 per cent, volatile matter content of 6.46 per cent, ash content of 52.37 per cent, pH of 10.50, C content of 86.28 per cent, N content of 3.25 per cent, P content of 3367.00 mg kg^{-1}, K content of 21.00, 340.00 mg kg^{-1}, Ca content of 6018.00 mg kg^{-1}, Mg content of 2976.00 mg kg^{-1}, Fe content of 1956.00 mg kg^{-1} and Mn content of 1560.00 mg kg^{-1} whereas palm kernel shell biochar had little moisture content, 12.29 per cent volatile matter content, 6.86 per cent ash content, pH of 6.90, 87.85 per cent C content, 1.11 per cent N content, 274.00 mg kg^{-1} P content, 1219.00 mg kg^{-1} K content, 19730.00 mg kg^{-1} Ca content, 131.00 mg kg^{-1} Mg content, 21380.00 mg kg^{-1} Fe content and 35.00 mg kg^{-1} Mn content.

Wabel *et al.* (2013) pyrolyzed *Conocarpus* wastes at 400^{0}C to investigate their impact on characteristics and chemical composition of biochars and concluded that the biochar produced had pH of 9.67, EC of 1.34 dS m^{-1}, C content of 76.83 per cent, N content of 0.87 per cent, S content of 1.72 per cent, K content of 0.54 g kg^{-1}, P content of 0.880 g kg^{-1} , K content of 0.540 g kg^{-1}, Ca content of 51.80 g kg^{-1} and Mg content of 3.98 g kg^{-1},

Slavich *et al.* (2013) produced biochar from cattle manure and municipal green waste, by pacific pyrolysis at highest treatment temperature (HTT) of 550°C, and at a heating rate of 5 to10°C min^{-1} and reported that farmyard manure biochar had pH of 9.70, EC of 1.60 dS m^{-1}, CEC of 13.00 cmol (+) kg^{-1}, total N content of 0.610 per cent, NH_4^+- N content of < 0.30 mg kg^{-1}, NO_3-N content of 0.330 mg kg^{-1}, total P content of 6900.00 mg kg^{-1}, total K content of 2.10 per cent, total Ca content of 1.50 per cent and total S content of 0.048 per cent, whereas greenwaste biochar had pH of 7.80, EC of 0.100 dS m^{-1}, CEC of 1.20 cmol kg^{-1}, total N content of 0.220 per cent, NH_4^+- N content of <0.30 mg kg^{-1}, NO_3^- N content of < 0.20 mg kg^{-1}, total P content of 190.00 mg kg^{-1}, total K content of 0.170 per cent, total Ca content of 0.170 per cent and total S content of 0.008 per cent.

Jha *et al.* (2013) reported that biochar pH ranged from 8.2 to 13, total C content varied from 33.0 per cent to 82.4 per cent. Biochar in general has low N content (0.18 to 2.0 per cent) and C: N ratio varied from 19 to 221.

Githinji (2014) evaluated the physico-chemical properties of peanut hulls biochar, produced by the slow pyrolysis method at 500°C and found that the biochar produced had alkaline pH of 8.60, surface area of 1.22 m^2 g^{-1}, ash content of 9.30 per cent, C content of 81.80 per cent, H content of 2.90 per cent, N content of 2.70 per cent, P content of 0.26 per cent and S content of 0.10 per cent.

Liu and Balasubramanian (2014) characterized biochar produced by the pyrolysis of coconut fiber and observed that C, H, N, K, S, Ca, Na, Fe and ash per cent were 67.51 per cent, 3.95 per cent, 1.01 per cent, 3.13 per cent, 0.370 per cent, 0.690 per cent, 0.240 per cent, 0.040 per cent and 9.18 per cent respectively.

2. 2. BIOCHAR AND SORPTION-DESORPTION OF NUTRIENTS

Biochar usually has greater sorption ability than natural soil organic matter due to its greater surface area, negative surface charge, and charge density (Liang *et al.*, 2006). Biochar can not only efficiently remove many cationic chemicals including a variety of metal ions, but also sorb anionic nutrients such as phosphate ions, though the removal mechanism for this process is not fully understood (Lehmann, 2007).

Manikandan and Subramanian (2013) conducted an experiment to study N release pattern of urea intercalated biochar derived from *Prosopis juliflora* using different forms of N *viz.*, NH_4^+, NO_3-, NH_2, combined NH_4^+ and NO_3^-, loaded at varying concentrations (20–200 mM) and sorption and desorption characteristics were examined. They reported that biochar can be used as a substrate to adsorb or desorb nutrients in order to evolve slow release or controlled release of fertilizers by exploiting its extensive surface area.

Zheng *et al.* (2010) determined the simultaneous sorption of ammonium and phosphate ions (NH_4^+ and PO_4^{3-}) by biochar using a batch equilibrium method. A fixed amount (100 mg) of biochar was placed into conical glass vials along with 10 ml of $NH_4H_2PO_4$ solutions. Biochars successfully removed NH_4^+ from aqueous solutions. The sorption capacity of the biochars for NH_4^+ was much higher than that on the activated carbon and other previous reported sorbents such as sepiolite (0.10 mmol g^{-1}) and acid treated slag (0.007 mmol g^{-1}) (Khelifi *et al* ., 2002).

Waters *et al.* (2010) investigated the charge of green waste biochar and cow manure biochar and its effect on ion retention and observed that Ca and Mg desorption increased with increasing shaking times for the green waste biochar.

Trakal *et al.* (2011) conducted a study to evaluate the sorption behavior of metals *viz.* Cd, Cu, Pb and Zn after biochar application into a metal-contaminated soil. Additionally, two different types of biochar originated from the same organic material (contaminated and uncontaminated) at different application rates (1 per cent and 2 per cent) were evaluated as a novelty of the experiment. Batch sorption-desorption experiments were established to compare the sorption behavior of metals originating from single- and multi-element solutions. Zn was easily desorbed in the presence of Cu, Pb and to a lesser extent by Cd. This desorption was reduced after biochar application. During multi-element sorption, Zn was significantly desorbed. The applied biochar enhanced Cu and Pb sorption also.

Dong *et al.* (2011) investigated the removal of Cr^{4+} from aqueous solutions using biochar from sugar beet tailing as a function of pH, contact time, and biochar mass via batch experiments and observed that the electrostatic attraction of Cr^{4+} to positively charged biochar surface, reduction of Cr^{4+} to Cr^{3+} ion, and complexation between Cr^{3+} ion and sugar beet tailing's functional groups were probably responsible for Cr^{4+} removal by sugar beet tailing's biochar.

Yao *et al.* (2011) evaluated 13 biochar materials to determine their potential to sorb NO_3^- from solution and it was found that four high temperature (600°C) biochars (bagasse, bamboo, peanut hull, and Brazilian pepperwood) were able to remove between 0.120 and 3.70 per cent NO_3^- (0.020 to 0.640 mg NO_3^- per g of biochar) from a solution (0.1 g: 50 ml of 34.40 mg l^{-1} NO_3^-) with variation in removal due to species of feedstock used. They also tested the significance of this NO_3^- retention mechanism, with respect to NO_3^- leaching using biochar @ 2 per cent into a sandy soil, in columns, and a nutrient solution was applied (34.40, 10.00, and 30.80 mg l^{-1} of NO_3^-, NH_4^+, and phosphate (PO_4^{3-}), respectively and it was found that the biochar materials reduced NO_3^- leaching by 34.00 per cent. They also found that 9 of the 13 biochars tested in their sorption experiment could remove NH_4^+ from solution (0.10 g biochar in 50 ml of 10 mg NH_4^+ l^{-1}), with removal rates ranging from 1.80 per cent to15.70 per cent (0.050 to 0.790 mg NH_4^+ per g biochar).

Dempster *et al.* (2012) applied biochar to a sandy soil and irrigated over 21 days and concluded that the cumulative NO_3^- leached was reduced by 25 per cent when compared with a control treatment and thus NO_3^- adsorbing biochars can reduce NO_3^- leaching. *Eucalyptus* sp. biochar (600°C) could adsorb NO_3^- when placed in an ammonium nitrate (NH_4NO_3) solution (10g: 100 ml), with up to 80 per cent adsorbed after 24 h when the NO_3^--N concentration was 2.50–5.00

mg NO_3^--N l^{-1} (0.02–0.04 mg NO_3^--N per g biochar), decreasing to 38 per cent at 50 mg NO_3^--N l^{-1} although the adsorbtion rate had increased to 0.19 mg NO_3^--N per g biochar.

Kameyama *et al.* (2012) also examined the permanence of adsorbed NO_3^- by measuring NO_3^- transport in soil columns amended with NO_3^-adsorbing bagasse biochar @ 5 per cent or 10 per cent by weight) and found that when a 20 mg N l^{-1} solution of KNO_3 was applied to the soil columns, the maximum concentration of NO_3^- in the effluent was 5.00 per cent less than in unamended soil.

2. 3. BIOCHAR AND GREENHOUSE GAS EMISSIONS FROM SOIL

Biochar consists of more than one fraction in terms of its stability, and it is usually divided into two pools: the "unstable matter" which decomposes on the order of days to months after application to soil (Smith *et al.*, 2009; Bruun *et al.*, 2010; Peng *et al.*, 2011), and the "stable matter" which remains over centuries to millennia.

Biochar is primarily composed of both single and condensed ring aromatic C, and subsequently has a mutual high surface area per unit mass and a high surface charge density (Lehmann, 2007). The biochars largely composed of single-ring aromatic and aliphatic C mineralize more rapidly in comparison to those composed of condensed aromatic C (Lehmann, 2007; Novotny *et al.*, 2007).

Relative to merely using fresh material to store C, because biochar decomposes over a long period of time, it is able to create the slow release of CO_2 into the atmosphere over an extended period, and thus reduce CO_2 emissions (Gaunt and Lehmann, 2008). Therefore, because biochar is able to gain CO_2 from the atmosphere, it would circumvent from the contribution of climate change, and hence aid in reducing global warming (Lehmann, 2007).

Yanai *et al.* (2007) conducted a laboratory incubation experiment by adding 10 per cent biochar to soil by weight and found that the effect of biochar on N_2O emissions was highly dependent on the moisture content of the soil. Shortly after rewetting dry soil to 73 and 78 per cent water-filled pore space, N_2O

emissions were reduced by 89 per cent when biochar was added, compared to the unamended control. However, when soil was rewetted at 83 per cent water-filled pore space, biochar-amended soils had approximately 50 per cent greater N_2O emissions.

Using a 2-pool first order decay model, Major *et al.* (2010b) calculated the mean residence time of biochar in soil, using data reported in incubation as well as field experiments. Mean residence times adjusted to a mean annual temperature of 10°C were calculated to be 3,300 yr for biochar added to an unmanaged savanna soil in Colombia, 1,300 yr for an incubation study using charcoal from old storage sites (Cheng *et al.*, 2006), 4,000 yr for biochar in *Terra preta* soils (Liang *et al.*, 2008), and 2,000 yr for ryegrass biochar added to soil (Kuzyakov *et al.*, 2009). Long-term modeling of the turnover of BC from savanna fires in Australia yielded estimated mean residence times of 1,300 and 2,600 year for a mean annual temperature of 27°C (Lehmann and Sohi, 2008).

Wardle *et al.* (2008) found no significant mass loss of buried biochar, over 10 years in the field, in the humus layer of a boreal forest. Spokas *et al.* (2009) found that the decomposition of biochar was nil when it was added to soil over 100 days in an incubation study, and Bruun *et al.* (2009) observed that straw biochar to decompose up to 18 times less than uncharred straw over 2 years, in the laboratory. Spokas *et al.* (2009) observed that application of biochar especially at higher rates (ranging from 5 per cent to 60 per cent by weight) caused a significant reduction in the net CH_4 consumption capacity of soil (meaning that actual CH_4 soil emissions were greater and CH_4 consumption was lesser when biochar was applied compared to the un-amended control.

Singh *et al.* (2008) suggested that rice cultivation in flooded systems produces significant amounts of CH_4, at least partly due to the anaerobic decomposition of crop residue in oxygen-limited conditions (Singh and Cowie, 2008). Using these crop residues to make biochar, could reduce emissions of CH_4 generated from their *in situ* decomposition, apparently without reducing soil organic C contents on the long term.

Spokas *et al.* (2009) also noticed a reduction in N_2O production when soil was amended with biochar in a laboratory incubation study over 100 days. This reduction was observed only at biochar application rates of 20, 40 and 60 per cent by weight, and no reduction was found at lower rates of 2 to 10 per cent by weight. Van Zwieten *et al.* (2009) also showed in an incubation study that adding 10 per cent biochar to soil by weight had the potential to greatly reduce N_2O emissions from soil shortly after rewetting at 70 per cent of the WHC of soil. In more recent work, Van Zwieten *et al.* (2010b), applied the equivalent of 10 and 50 t ha^{-1} of several contrasting biochar materials to a poor soil in a laboratory experiment and all the biochars at both application rates significantly reduced N_2O emissions from flooded soil (by up to 84 per cent), compared to un-amended control, but the different biochar treatments did not significantly differ among themselves. Singh *et al.* (2010) added the equivalent of 10 t ha^{-1} of several different biochar materials to two soil types (Vertisol and Alfisol) in a laboratory experiment, and found that biochar application to soil could, under certain conditions, lead to reductions in N_2O production by soil. Most effective materials were those made from wood and from poultry litter at 550°C with steam activation. Poultry litter biochar made at 400°C and not activated actually yielded greater N_2O emissions than the control over the first 4 months of the experiment. During the 5th and last month of the trial, all biochar materials reduced N_2O emissions from both soils by up to 73 per cent compared to unamended controls, indicating that this beneficial effect of biochar improves with time

Clough and Condron (2010) studied the effect of applying 20 t ha^{-1} of a wood-derived biochar on N_2O production by a pasture soil after the addition of bovine urine, in the laboratory. Over 53 days, N_2O production was not statistically different whether or not biochar had been applied to soil. These authors also did not observe a reduction in the pool of inorganic N in the soil, which is the precursor to the formation of N_2O, when biochar was applied.

Woolf *et al.* (2010) predicted that sustainable biochar systems could amount to net avoided emissions of up to 1.80 Gt CO_2 a year (12 per cent of current emissions), for total net avoided emissions of 130 Gt CO_2 over 100 years.

In an incubation study, Van Zwieten *et al.* (2010a) observed lower soil respiration rates when several contrasting biochar materials were added to an acidic soil, compared to unamended controls.

Kimetu and Lehmann (2010) measured soil respiration in a field experiment where biochar as well as green manure were applied at 6 t C ha^{-1} and reported that on soil with low organic C contents, biochar resulted in a reduction in C loss by respiration by 27 per cent compared to the unamended control, while the green manure resulted in a 22 per cent increase in C loss by respiration. On C-rich soil, neither amendment resulted in significantly greater soil respiration losses compared to the unamended control. In plots receiving biochar, 6.80 times more C was found in the intra-aggregate fraction per unit C respired, when compared to plots where green manure had been applied. This suggests that apart from being more stable chemically, biochar may be more efficiently stabilized in soil (Kimetu and Lehmann, 2010). Major *et al.* (2010b) also found much greater amounts of non-biochar C loss by respiration over 2 years when biochar was applied.

Zhang *et al.* (2010) found that applying wheat straw biochar @ 10 to 40 t ha^{-1}fields can reduce N_2O emissions in flooded paddy. Karhu *et al.* (2011) carried out an organically managed field experiment in Finland by applying birch biochar @ 9 t ha^{-1} before sowing wheat and measured gas fluxes on 9 occasions until canopy closing and observed that immediately after addition to soil, biochar caused significantly greater CH_4 uptake by soil, and thus 96 per cent less emissions when compared to the control.

2. 4. EFFECTS OF BIOCHAR APPLICATION ON CROP PRODUCTION

2. 4. 1. Effects of Biochar Application on Physical Properties of Soil

Biochar is highly porous, thus its application to soil is considered to improve a range of soil physical properties including total porosity, pore size distribution, soil density, soil moisture content, water holding capacity or plant available water content (PAWC), and infiltration or hydraulic conductivity (Major *et al.*, 2009; Atkinson *et al.*, 2010).

Biochar is predicted to increase the WHC of soil because of increases in particle surface area and storage of water within its porous structure (Lehmann *et al.*, 2003). Chan *et al.* (2007) showed that biochar application in the soil improved soil physical properties *viz.* soil aggregation and WHC. Asai *et al.* (2009) found an increase in WHC by applying biochar @ 9 t ha^{-1} or 16 t ha^{-1}. Masulili *et al.* (2010) conducted an experiment where WHC was increased from 11.3 per cent for untreated control soil to 15.5 per cent for soil treated with rice husk biochar. Sokchea and Preston (2011) and Southavong and Pretson (2011) reported an increase in WHC of soil from 43 to 53 per cent and 40 to 50 per cent, respectively, as a result of biochar application. A positive improvement of WHC was also reported by Karhu *et al.* (2011).

Verheijen *et al.* (2010) proposed that direct pore contribution from biochar potentially increased water storage between −10,000 and −1,000,000 kPa and thus potentially increased the number of pores between 0.03 μm and 0.0003 μm diameters in the amended soil. They also suggested that biochar application may improve aggregate stability and thus soil porosity.

Jones *et al.* (2010) reported that application of 40 and 80 t ha^{-1} of green waste biochar to bauxite processing residue coarse sand significantly decreased macroporosity (pore diameters >29 μm) whilst significantly increased mesoporosity (pore diameters between 0.20 and 0.29 μm). Increased mesoporosity was attributed to the biochar partly filling large voids between the coarse sand particles. Evidence from pot trials also suggested that short-term changes in pore-size distribution following biochar application may result from aggregate settling and thus changes to accommodation pores (Novak *et al.*, 2012). Belyaeva and Haynes (2012) also found that addition of biochar at the high rate (50 or 100 t ha^{-1}) greatly decreased macroporosity and increased mesoporosity and in some cases microporosity. As a result, the available WHC was increased substantially.

Zhang *et al.* (2010) observed that the application of wheat straw biochar decreased the bulk density of a rice paddy soil at 40 t ha^{-1}. Liu *et al.* (2012)

reported that the application of 8-16 g kg^{-1} of sawdust biochar significantly increased the aggregate stability.

Application of acacia green waste biochar at 47 t ha^{-1} significantly reduced soil bulk density and thus increased total porosity and saturated water content (Hardie *et al.*, 2014). They proposed that biochar application may influence soil porosity and thus soil water retention via three mechanisms (1) direct pore contribution from pores within the biochar, (2) creation of packing or accommodation pores between biochar and the surrounding soil aggregates, and (3) through improved persistence of soil pores due to increased aggregate stability.

Githinji (2014) evaluated the effect of biochar application rate on soil physical and hydraulic properties of a sandy loam amended at different rates (25, 50, 75, and 100 per cent v/v) of biochar. The results showed that bulk density decreased from 1.325 to 0.363 g cm^{-3} with porosity increasing from 0.500 to 0.773 cm^3 cm^{-3}. The mean volumetric water content ranged from 3.90 to 14.00 cm^3 cm^{-3}, while the wilting rate of tomato ranged from 4.67 to 9.50, respectively, for the non-amended soil and 100 per cent biochar-amended soil. These results strongly suggest positive improvement of soil physical and hydraulic properties following addition of biochar amendment.

Ippolito *et al.* (2012) reported that a 2 per cent biochar addition, by weight, increased the moisture content of two Aridisols, by 3 to 7 per cent relative to control soils, and when relevant evapo-transpiration rates were considered, it was concluded that this could lead to an additional 0.40 to 2.50 days of available water for crop growth. Kameyama *et al.* (2012) found that when a bagasse biochar (800 °C) was applied at a rate $\geq$ 5 per cent by weight to a calcareous dark red soil the saturated hydraulic conductivity increased, with the effect likely to also be a function of the meso- and micro-pore fractions in the soil and biochar. Biochar is a porous, C rich (80 per cent) compound which is highly resistant to decay. Its structure enables it to store both water and nutrient elements, and, for this reason, it is being considered as a defense against drought (Novak *et al.*, 2009; Major *et al.*, 2010).

2. 4. 2. Effects of Biochar Application on Chemical Properties of Soil

Biochar is typically an alkaline material and has been shown to increase the pH of acidic soils to levels optimal for crop growth (pH of 6 to 7). When biochar has high concentrations of carbonates, it may have effective liming properties for overcoming soil acidity (Chan and Xu, 2009). A positive effect of biochar in improving soil pH was observed by Rodriguez *et al.* (2009), where the pH of an acid soil increased from 4.60 to 6.30 with addition of 5 per cent biochar to the soil. Van Zwieten *et al.* (2010a) tested two biochars produced from papermill waste with pH values 8-9 and a liming value around 30 per cent that of $CaCO_3$. When 10 t ha^{-1} of these biochars was added to a Ferralsol soil in a greenhouse experiment, the pH rose from 4.20 to 5.90.

Ippolito *et al.* (2012) also showed that biochar increased the CEC of the soil, and this was associated with soil fertility improvement and decreased fertilizer runoff. Masulili *et al.* (2010) also reported that application of biochar from rice husk at 10 t ha^{-1} in a very acid soil increased pH from 3.75 to 4.40. Jeffery *et al.* (2011) noted a soil pH increase of 0.10 to 2.0 units after biochar was applied to soils that have a wide range of pH values. Southavong and Preston (2011) where the soil pH increased from 4.50 to 5.13 and 5.40 when biochar was added to soil at 2.00 to 8.00 per cent with the higher value for biochar from the stove than from the down draft gasifier. Masto *et al.* (2013) conducted a field experiment in an acidic red soil to investigate the effects of lignite fly ash and biochar on soil nutrients, biological properties, and the yield of maize and concluded that BC @ 2 t ha^{-1} and 4 t ha^{-1} increased pH from 6.09 in control to 6.64.

Increase in CEC of up to 40 per cent over initial CEC by addition of biochar was reported by Topoliantz (2002). Many authors *viz.* Liang *et al.* (2006) and Yamato *et al.* (2006) have also reported an increase in soil CEC through application of biochar. Liang *et al.* (2006) conducted an experiment to compare the properties of biochar-rich Anthrosols from the Brazilian Amazon (ages between 600 and 8700 year BP) and the adjacent non-BC soils and concluded that CEC per unit soil C were up to 1.90 times higher in Anthrosols than in the adjacent soils. The charge density (potential CEC per unit surface area) was greater in BC-rich Anthrosols than adjacent soils. Additionally, a high SSA was attributable to the presence of biochar, which may contribute to the high CEC found in soils that are rich in biochar. Anthrosols contained soil organic matter with 55 to 238 per cent higher levels of aromaticity than adjacent soils and thermal oxidation were 23 to 355 per cent greater in Anthrosols than adjacent soils.

Lehmann and Rondon (2006) reviewed 24 studies with soil biochar additions and found improved productivity in all of them ranging from 20 to 220 per cent at application rates of 0.40 to 8 t C ha^{-1}. Such increases in productivity were explained by improving soil chemical, biological and physical properties. Nutrient retention in soils amended with biochar may be attributed to the sorptive capacity of fresh biochar through charge or covalent interactions (Major *et al.*, 2009). Rondon *et al.* (2007) performed an experiment to examine the potential, magnitude and causes of enhanced biological N_2 fixation by common beans (*Phaseolus vulgaris* L.) through biochar additions and concluded that biochar @ 90 g kg^{-1} increased the proportion of fixed N from 50 per cent to 72 per cent and improved the availability of P, K, Ca, B and Mo.

Van Zwieten *et al.* (2010a) assessed the effects of biochar from slow pyrolysis of paper mill waste on agronomic performance and soil fertility in a glass house study and reported that application of biochar @ 10 t ha^{-1} in a ferrosol significantly increased pH from 4.20 to 5.93 and CEC increased from 4 cmol (+) kg^{-1} to 10.5 cmol (+) kg^{-1}. The exchangeable Ca levels increased from 1.23 cmol (+) kg^{-1} to 8.87 cmol (+) kg^{-1} and total soil carbon was significantly increased to around 0.50 per cent. Major *et al.* (2010a) studied the effect of a single application of 0, 8 and 20 t ha^{-1} of biochar to a Colombian savanna Oxisol for 4 years (2003 to 2006) and the results showed that the availability of nutrients such as Ca and Mg was 77 to 320 per cent greater with biochar. Soil pH increased, and exchangeable acidity showed a decreasing trend with biochar application. Sukartono *et al.* (2011) conducted an experiment to evaluate the effect of biochar application on soil fertility status, nutrient uptake and yield of maize in sandy soils of Indonesia and the study revealed that application of biochar @ 15 t ha^{-1} increased the soil organic C from 0.90-1.20 per cent. pH, CEC, available P, exchangeable K, Ca, Mg, nutrient uptake and yield were also increased.

Sika (2012) conducted a leaching experiment in sandy soils using biochar and concluded that biochar application @ 0.50, 2.50, and 10.0 per cent w/w significantly reduced the leaching of ammonium (12, 50 and 86 per cent respectively) and nitrate (26, 42 and 95 per cent respectively) fertilizer from the sandy soil. Moreover, biochar (0.50 per cent) significantly reduced the leaching of basic cations, phosphorus and certain micronutrients. Southavong *et al.* (2012) investigated the effect of biochar and biodigester effluent on biomass yield of water spinach and on soil fertility and concluded that application of biochar @ 40 t ha^{-1} increased WHC of the soil by 40-60 per cent and soil pH increased from 4.68 to 6.22. Huang *et al.* (2013) conducted an experiment to quantify the effect of biochar amendment on soil quality and crop productivity in Chinese rice paddies and concluded that the addition of biochar @ 10, 20 and 40 t ha^{-1} to paddy soils led to increase in SOC by 33 per cent, soil pH by 6 per cent and soil total N by 10 per cent, and a decrease in soil bulk density by 9 per cent, on average, compared with untreated soils.

Masto *et al.* (2013) conducted a field experiment in an acidic red soil to investigate the effects of lignite fly ash and biochar on soil nutrients, biological properties, and the yield of maize. Application of biochar @ 2 and 4 t ha^{-1} increased soil P and K availability by 110 and by 64 per cent respectively. Soil enzymes like dehydrogenase activity (+ 60.70 per cent), alkaline phosphatase (+32.20 per cent), fluorescein hydrolases activity (12.30 per cent) and microbial biomass (+25.30 per cent) increased. The addition of biochar alone and in combination with lignite fly ash has significantly increased the soil organic C from 0.813 per cent in control to 1.17 and 1.00 per cent at biochar and biochar + lignite fly ash treatment, respectively.

Islami *et al.* (2011) while studying the yield stability of cassava planted in intercropping system after 3 years of biochar application found that biochar @ 15 t ha^{-1} improved soil fertility status, as shown by an increase of soil organic C, CEC and per cent of water stable aggregates. Jien and Wang (2013) conducted an incubation study to evaluate the influences of biochar on the physico-chemical and biological properties of long-term cultivated, acidic Ultisol and suggested that application of biochar @ 2.50 and 5.00 per cent improved the physico-chemical and biological properties of the highly weathered soils, including significant increases in soil pH from 3.90 to 5.10, CEC from 7.41 to 10.8 cmol (+) kg^{-1}, base cation percentage from 6.40 to 26.0 per cent, and microbial biomass carbon (MBC) from 835 to 1262 mg kg^{-1}. Biochar application decreased bulk density from 1.40 to 1.10 g cc^{-1} and increased the mean weight diameter (MWD) of soil aggregates from 2.60 to 4.00 cm. Incorporating biochar into the soil @ 2.50 and 5.00 per cent significantly reduced soil loss by 50 per cent and 64 per cent respectively, compared with the control. The formation of macro-aggregates in the biochar-amended soils is the critical factor to improve soil erosion potential. Based on these results, 5.00 per cent application rate of biochar is considered as suitable for highly weathered soil because this application rate efficiently improves soil physico-chemical properties and reduces soil loss.

Chintalaa *et al.* (2014) investigated the effect of biochar addition on the chemical properties of acidic soil such as soil pH, EC, CEC and exchangeable acidity by incubating acidic soil (clayey, smectitic, acid, mesic, shallow, Aridic Ustorthent) of pH < 4.80 with biochars for 165 days. The biochars were produced from two biomass feedstocks such as corn stover and switchgrass and were applied @ 52, 104, and 156 t ha^{-1} to acidic soil. Corn stover biochar significantly increased EC of acidic soil by 21, 40 and 83 per cent as application rate increased from 52, 104, and 156 t ha^{-1}, respectively, whereas the switchgrass biochar had increased the EC of soil by 19, 51 and 57 per cent at application rates of 52, 104, and 156 t ha^{-1}, respectively. Soil pH was significantly increased by 0.73, 0.99, and 1.36 units with the application of corn stover biochar at 52, 104, and 156 tha^{-1}, respectively, whereas the switchgrass biochar application increased soil pH by 0.49, 0.74, and 0.91 units at application rates of 52, 104, and 156 t ha^{-1}, respectively. The rate of pH increase was significantly higher in corn stover biochar compared to switchgrass biochar.

Widowatil and Asnah (2014) conducted a field experiment to study the effect of biochar @ 30 t ha^{-1} prepared from organic waste, on K fertilizer leaching and uptake, efficiency and effectiveness of K fertilization, and economic viability of farming maize in an inceptisol. The results suggested that biochar could replace and reduce KCl fertilizer. Biochar application increased the availability of nutrients by 69 to 89 per cent for K^+, 61 to 70 per cent for Ca^{2+}, 39 to 53 per cent for N total, 179 to 208 per cent for P.

2. 4. 3. Effect of Biochar on Soil Biological Properties

The large porosity of biochar provides surfaces for soil microbes to colonize and grow, where their predators cannot access them (i.e. the "refuge" hypothesis). Futhermore, the fact that these surfaces sorb inorganic nutrients well as organic substances and gases that might provide ideal environments for microbes. While the pore size range varies in biochar, it is generally adequate for a range of soil microorganisms to colonize (Thies and Rillig, 2009).

Biochar-induced increases in soil microbial biomass can be beneficial for agriculture for three main reasons (Thies and Rillig, 2009). Firstly, soil microbes are responsible for the process of nutrient cycling, whereby, soil organic matter is consumed and transformed (mineralization) into compounds that are available for plant uptake. Secondly, the decay of soil microbial biomass contributes to the soil organic C pool, which is important for soil fertility. Thirdly, some beneficial soil microorganisms, such as mycorrhizal fungi, engage in symbiotic relationships with plants by forming either intracellular (AMF) or extracellular (ectomycorrhizal fungi) connections with plant roots.

Ogawa and Yamaba (1986) had used biochar as a carrier substrate for both *Rhizobia* and for AMF over the past 20 years with excellent success. Additional studies conducted in Japan (Takagi and Yoshida, 2003) and in Syria by Beck (1991) had shown that biochar is a suitable carrier for the N_2-fixing root nodule bacteria *Rhizobium, Mesorhizobium* and *Bradyrhizobium.*

Graber *et al.* (2010) found better pepper growth and fruit yield in soil-less, coconut-fiber based substrate amended with 1 to 5 per cent biochar by weight. Tomato height and leaf size were also greater but not fruit yield. The beneficial effect of biochar was not attributed to better nutrition or water relations in the plants. However, greater amounts of culturable rhizosphere and bulk substrate microbes usually found in soil were present when biochar was applied and pepper was grown.

Graber *et al.* (2010) also reported that *Trichoderma* sp. and root-associated yeast were not detected in unamended substrate and increased by 2-3 orders of magnitude in the biochar-amended substrate. Overall, significantly greater numbers of fungi, bacteria and *Pseudomonas* sp. were found in biochar-amended and the beneficial effect of biochar on microbe abundance was more pronounced in the rhizosphere than the bulk potting substrate. Molecular analyses indicated that 16 of the 20 microbial isolates from biochar-amended treatments corresponded to plant growth promoting and biocontrol agents and these microbes could have played a role in improving yields with biochar.

2. 4. 3. 1.Biochar and Biological N Fixation

Biochar additions not only affect microbial populations and activity in soil, but also plant–microbe interactions through their effects on nutrient availability and modification of habitat. *Rhizobia* spp. living in symbiosis with many legume species is able to reduce atmospheric N_2 to organic N through a series of enzymatic reactions (Giller, 2001).

With large biochar concentrations, available nitrate concentrations are usually low and available Ca, P and micronutrient concentrations are high, which is ideal for maximum BNF (Lehmann *et al.*, 2003). Indeed, BNF by common beans, as determined by ^{15}N dilution, increased from 50 to 72 per cent of total N uptake with increasing rates of bio-char additions (0, 31, 62, and 93 t C ha^{-1}) to a low-fertility Oxisol.

In addition to changing nutrient availabilities that are conducive to high BNF, inoculation with *Rhizobia* may be more effective in presence of biochar due to the habitat offered by the biochar. In fact, several studies indicate that biochar is an excellent support material for Rhizobium inoculants (Lal and Mishra, 1998). Consequently, BNF determined by N difference was found to be 15 per cent higher when biochar was added to soil at early stages of alfalfa development and 227 per cent higher when nodule development was greatest (Nishio and Okano, 1991)). Biochar additions are, therefore, able to increase the net input of N into agricultural landscapes.

Lehmann *et al.* (2003) showed that while biomass production and N uptake of cowpea increased through large amounts of biochar additions, plants' N nutrition decreased. With appropriate application rates of bio-char and supplementary nutrient additions, N input to agricultural systems can be increased without decreasing plant productivity. Such a soil management system may be interesting in the context of mixed legume–cereal intercropping or of agro-forestry with woody legumes. Soil nitrogen stocks and eventually nitrogen availability can be increased and be made available to the nonlegume in a rotational system.

Applications of biochar (Gundale and DeLuca, 2006) can increase nitrification. The biochar micro-environment may also provide a favourable niche (fine structural pores) in which oxygen concentration declines; for nitrogenase to function effectively, low oxygen tensions are required with Fe and Mo ions (Thies and Rillig, 2009).

Diazotrophs fix atmospheric N in soil either freely or in symbiotic associations with leguminous plants. Free-living N fixers, would benefit from a reduced partial pressure of oxygen in the small pores of biochar (since oxygen destroys enzymes required for the biological fixation of N). Also, if Fe and Mn are sufficiently available, free-living N fixers could be favoured on and in biochar particles. Biochars are generally low in inorganic-N and this can provide diazotrophs with a competitive advantage for colonization of the biochars large surface area. This factor combined with biochar's potential for NH_4^+ exchange with the soil solution could modify soil-N availability to the plant and stimulate nodulation and fixation. A role has been suggested for biochar in adsorbing and protecting chemical signalling molecules derived from plants such as the nod factors which enhance root nodulation via Rhizobia (Thies and Rillig, 2009).

Ishwaran *et al.* (1980) used biochar as carrier material for *Rhizobium*. Biochar provides favorable reaction and aeration and enhances the longevity of these bacteria. Ogawa (1994) noted that adding biochar to soil seemed to stimulate the activity of free-living N fixers, which might be more competitive relative to other organisms on biochar surfaces as not supplied by biochar.

Rondon *et al.* (2007) grew common beans on an acidic tropical soil, and through the use of isotopically labelled N fertilizers they assessed amounts of N in bean biomass originating from inorganic soil N or atmospheric N fixation. They found that the proportion of N derived symbiotically increased and the proportion of N derived from the soil decreased as more biochar was applied. However, biomass yield and total N uptake decreased at the higher biochar application rate (90 g kg-1). The positive effects of biochar, including increased N fixation, led to 30 to 40 per cent increase in bean yield with biochar additions upto 50 g kg^{-1}. Rhizobia show increased function in neutral pH soils, so increasing alkalinity in acidic soil enhances nodulation and fixation.

*2. 4. 3. 2. **Effect of Biochar on Mycorrhizae***

Biochars can also increase endomycorrhizal plant associations, enhancing P availability (Garcia-Montiel *et al.*, 2000). Warnock *et al.* (2007) reviewed the literature on biochar effects on AMF, ectomycorrhizal fungi as well as ericoid mycorrhizal fungi abundance and interactions with plants and found usually positive impacts. They proposed 4 mechanisms by which biochar could favour plant-mycorrhizal interactions and mycorrhizae abundance. The first relates to the improvement of soil physico-chemical properties, including better availability of nutrients. Better availability of nutrients which limit fungal growth could favour mycorrizal fungi, and plant-mycorrhizal interactions could also be favoured by certain changes in available nutrient ratios, for example the available N: P ratio. Secondly, biochar could change the activity of other microbes which have an impact on mycorrhizae. Mycorrhization helper bacteria and phosphate solubilizing bacteria, for example, could find refuge on biochar particles and in turn promote the functions of mycorrhizae. Third, biochar could alter the signalling between host plants and mycorrhizae, or it could detoxify allelochemicals. Changes in the abundance of such compounds can have important impacts on the growth of mycorrhizal fungi and the development of plant-microbe symbioses. Biochar could both sorb and release signalling and allelopahtic compounds, but given that this could be both beneficial (e.g. in thwhere allelochemicals are detoxified) or detrimental (e.g. if biochar "sequesters" signalling compounds which would stimulate infections by mycorrhizae).

Much work has been carried out by the Japanese relating to biochar's effects on mycorrhizae, and positive impacts of biochar amendments on the infection of crop roots by mycorrhizae (Nishio and Okano, 1991). The colonization rates by mycorrhizal fungi were enhanced in the majority of experiments conducted (Warnock *et al.*, 2007). Solaiman *et al.* (2010) directly observed that biochar applied in bands in a dryland wheat field encouraged mycorrhizal root colonization of the crop in the year after application, and residual effects were also observed 2 years later. In the year after biochar application improved mycorrizal colonization was linked to improved crop yield not because of improved P nutrition, which was not expected to be limiting, but to greater water foraging.

Ishii and Kadoya (1994) reported that application of biochar @ 800 g m^{-3} enhanced the mycorrhizal response by 610 per cent in citrus. They conducted another experiment to study the effect of 3 biochar types on AMF (*Glomus fasciculatum*) in river sand and concluded that biochar @ 2 per cent increased the mycorrhizal response by 540 per cent and the overall P availability also increased. Matsubara *et al.* (2002) studied the effect of biochar on AMF, Fusarium and Aspergillus and reported that biochar @ 10 per cent and 30 per cent enhanced the mycorrhizal response by 50 per cent and 69 per cent respectively and thus there was improved pathogen resistance.

Yamato *et al.* (2006) observed an increase in the root amount and colonization rate of AMF on maize after bark charcoal application. Husk and Major (2010) performed a field study in Quebec, Canada and observed that biochar @ 3.90 t ha^{-1} resulted in increased root colonisation by ectomycorrhizae in the forage crop.

2.5.EFFECT OF BIOCHAR APPLICATION ON PLANT GROWTH, NUTRIENT UPTAKE AND YIELD

Lehmann (2007) stressed that nutrients in the soil are retained and remain available to plants due to the application of biochar hence it increased crop yield. It has been well documented that biochar amendment to crop lands enhances crop productivity through improving soil quality (Asai *et al.,* 2009; Sohi *et al.,* 2010; Van Zwieten *et al.,* 2010a; Gaskin *et al.,* 2010; Haefele *et al.,* 2011).

Biochar can improve plant productivity directly as a result of its nutrient content and release characteristics, as well as indirectly, via: (i) improved retention of nutrients (Lehmann *et al.*, 2003); (ii) improvements in soil pH (Rondon *et al.*, 2007); (iii) increased soil CEC (Liang *et al.*, 2006); (iv) improved soil physical properties (Chan *et al.*, 2008), including an increase in soil water retention (Laird *et al.*, 2010); and (v) alteration of soil microbial populations and functions (Pietikainen *et al.*, 2000). These effects may also act in concert to result in improved crop performance.

A liming effect of biochar has been suggested in literature as one of the likely reasons for improved crop yields on acidic soils (Verheijen *et al.*, 2010). Improved crop yields have also been attributed to a 'fertilizer effect' of added biochar and ash, supplying important plant nutrients such as K, N, Ca, and P. Biochar typically increases pH of acidic soils (Lehmann *et al.*, 2003; Gaskin *et al.*, 2010; Van Zwieten *et al.*, 2010a) due to the liming capacity of associated carbonate salts retained in the ash component of biochar. This can improve the availability of some nutrients, which is commonly thought to be responsible for positive plant growth responses to biochar amendments (Chan and Xu, 2009).

A combination of biochars ability to raise soil pH (Hoshi, 2001; Yamato *et al.*, 2006; Rondon *et al.*, 2007) improve physical properties such as water holding capacity and retain soil nutrients and reduce leaching losses (Hoshi, 2001; Lehmann *et al.*, 2003; Lehmann, 2007) likely contribute to its ability to increase plant productivity.

Fresh biochar has been reported to have both direct and indirect influence on soil nutrient availability (Blackwell *et al.*, 2009; Chan and Xu, 2009), which can have impacts on plant growth. Direct effects are largely associated with the retained feedstock nutrients in biochar, and are apparent when soil nutrients, plant production, and foliar nutrient concentrations are enhanced with biochar applications (Lehmann *et al.*, 2003; Gaskin *et al.*, 2010).

Yield increases with biochar application have been documented in controlled environments as well as in the field (Lehmann and Rondon, 2006; Blackwell *et al.*, 2009; Chan and Xu, 2009; Asai *et al.*, 2009). Reported biochar application rates ranged from less than 1 t ha^{-1} to over 100 t ha^{-1}, and reported percent yield increases over comparable controls ranged from less than 10 per cent to over 200 per cent. Biochar applications to soils may increase seed germination, plant growth, and crop yields (Lehmann *et al.*, 2003; Rondon *et al.*, 2007; Graber *et al.*, 2010).

It is likely that the optimum rate of biochar application will vary and needs to be determined for each soil type and target plant species. Beneficial effects on crop yields have been documented in a number of pot and field trials (Chan *et al.*, 2007; Chan *et al.*, 2008; Asai *et al.*, 2009; Major *et al.*, 2010b; Van Zwieten *et al.*, 2010a)

Chan *et al.* (2007) found that additions of biochar plus fertilizer (NH_4^+) increased radish yields more than the addition of fertilizer alone, indicating reduced N leaching and increased N use efficiency (Chan *et al.*, 2007). Lehmann (2007) reported increasing yields with increasing biochar applications of up to 140 t ha^{-1} on highly weathered soils in the humid tropics, for most of their tests.

They concluded that 'crops respond positively to bio-char additions up to 50 Mg ha^{-1} and may show growth reductions only at very high applications'.

Lehmann *et al.* (2003) conducted an experiment to study the nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the central Amazon basin and reported that Anthrosol that received biochar @ 67.60 and 135.20 t ha^{-1} C showed significantly higher P, Ca, Mn, and Zn availability than the Ferralsol increasing biomass production of both cowpea and rice by 38 to 45 per cent without fertilization.

Rondon *et al.* (2005) found that biomass growth of beans (*Phaseolus vulgaris* L.) rose with biochar applications up to 60 t ha^{-1} but fell to the same value as for control plots when biochar application was increased to 90 t ha^{-1}.

On a Brazilian amazon oxisol, Steiner *et al.* (2007) observed a progressive increase in the beneficial effect of biochar amendment on grain yield over time in a rice-sorghum cropping system. After four growing seasons over 2 years, cumulative yield of rice and sorghum was increased approximately by 75 per cent, when 11 t ha^{-1} biochar was applied at the beginning of the experiment. In a degraded Kenyan Oxisol, Kimetu *et al.* (2008) found a doubling of cumulative maize yield after three repeated biochar applications of 7 t ha^{-1} over 2 years.

Rondon *et al.* (2007) conducted a study to examine the potential, magnitude, and causes of enhanced biological N_2 fixation (BNF) by common beans (*Phaseolus vulgaris* L.) through biochar. Biochar was added at 30, 60, and 90 g kg^{-1} soil and observed that the proportion of fixed N increased from 50 per cent without biochar additions to 72 per cent with 90 g kg^{-1} biochar added. While total N derived from the atmosphere (NdfA) significantly increased by 49 and 78 per cent with 30 and 60 g kg^{-1} biochar added to soil, respectively, NdfA decreased to 30 per cent above the control with 90 g kg^{-1} due to low total biomass production and N uptake. Bean yield increased by 46 per cent and biomass production by 39 per cent over the control at 90 and 60 g kg^{-1} biochar, respectively.

Bounsuy (2010) reported that application of biochar @ 20t ha^{-1} and 40 t ha^{-1} resulted in ayield of 1.82 t ha^{-1} and 3.76 t ha^{-1} respectively in rice at

Cambodia. According to Zhang *et al.* (2010), biochar amendment @ 10 and 40 t ha^{-1}increased the rice yield by 12 per cent and 14 per cent in unfertilized soils and by 8.80 per cent and 12.10 per cent in the soil with N fertilization.

Similar result was also reported by Major *et al.* (2010a), who studied the effect of biochar addition to a Colombian savanna oxisol for 4 years in a maize-soybean cropping system, and observed that maize yield did not significantly increase in the first year, but increases in the 20 t ha^{-1}plots over the control were 28, 30, and 140 per cent for second, third, and fourth year, respectively. The greater crop yield and nutrient uptake was primarily attributed to the 77 to 320 per cent greater available Ca and Mg in soil where biochar was applied.

Major (2010b) performed another field study in Quebec, Canada and reported that biochar @ 3.90 t ha^{-1} resulted in 19 per cent increase in Soybean yield over the control, while the forage biomass was doubled. Uzoma *et al.* (2011) conducted a glasshouse experiment where a biochar manufactured from cow manure (500°C) was applied at increasing application of biochar to a sandy soil, subsequently planted with maize. Both maize yield and N uptake increased with increasing biochar rate, indicating N release from biochar. However, Singhal *et al.* (2011) showed that application of rice-husk-biochar @ 2 t ha^{-1} increased the grain yield from less than 4 t ha^{-1} for the control treatment to more than 5 t ha^{-1} for the biochar treatment.

Southavong *et al.* (2012) reported that application of biochar to soil @ 40 t ha^{-1}increased plant height, number of leaves, leaf width and foliage yield of water spinach (18.10 t ha^{-1}) in both first and second harvests. Liu *et al.* (2012) reported that biochar @ < 30 t ha^{-1}, increased crop productivity by 11.00 per cent on average, while the responses varied with experimental conditions. Greater responses were found in pot experiments than in field, in acid than in neutral soils, in sandy textured than in loam and silt soils. Crop response in field experiments was greater for dry land crops (10.60 per cent on average) than for paddy rice (5.60 per cent on average). Generally, greater positive responses were found in experiments with legumes, vegetables and grasses. The average increase in crop productivity was 30.30, 28.60, and 13.90 per cent respectively for legume crops, vegetables, and grasses and 8.40, 11.30, and 6.60 per cent respectively for maize, wheat, and rice. Yield increases with biochar were greater than biomass increases for maize, whereas, the reverse was true for wheat.

Zheng *et al.* (2012) conducted a pot culture experiment to study N uptake by maize in the same soil with biochar addition at the rates of 1 per cent, 2 per cent or 5 per cent (w/w). No additional N fertilizer was added into the soil. The length, volume, surface area and tips of maize roots were significantly increased by 78.20 to 128.20 per cent, 36.60 to 58.90 per cent, 30.20 to 67.30 per cent and 7.80 to 42.90 per cent, respectively. Slavich *et al.* (2013) reported that feedlot manure biochar @ 10 t ha^{-1} increased total pasture productivity by 11 per cent and improved the agronomic nitrogen use efficiency (NUE) by 23 per cent in acidic ferralsols.

Saxena *et al.*(2013) conducted a pot experiment with 6 different treatments *viz.* pure soil, soil + biochar @ 15 g kg^{-1} of soil, soil + *Bacillus* sp., soil + biochar + *Bacillus* sp., soil + biochar + commercial biofertilizer (Biozyme), and soil + chemical fertilizer to study the impact of addition of biochar along with *Bacillus* sp. on growth and yield of french bean and observed that addition of biochar to soil influenced the overall growth of plants positively but the inoculation with *Bacillus* sp. enhanced this effect further. The treatment, soil + biochar + *Bacillus* sp. also showed the highest number of phosphate solubilizing bacteria in the rhizosphere of plants and percent N content in shoots, whereas the highest P content was observed in soil + DAP, followed by soil + biochar + *Bacillus* sp. combination. The root length and root and shoot biomass were significantly higher, 14.88 cm, 1.85 g and 3.22 g, respectively in the treatment consisting of soil, biochar and *Bacillus* sp. as compared to 10.68 cm, 0.89 g and 1.62 g in un-inoculated control. Masto *et al.* (2013) conducted a field experiment in an acidic red soil to investigate the effects of lignite fly ash (LFA) and biochar on soil nutrients, biological properties, and the yield of maize. BC @ 2 t ha^{-1} and 4 t ha^{-1} increased maize grain yield increased by 11.40 per cent for BC, 28.10 per cent for BC + LFA treatment, and the yield was not significantly affected for the LFA alone treatment.

Islami *et al.* (2011) carried out a field experiment to study the yield stability of cassava planted in cassava + peanuts intercropping systems after 3 years of biochar application and observed that addition of both FYM @ 20 t ha^{-1} and biochar @15 t ha^{-1} improved soil quality and increased crop yield. Application of biochar increased and stabilized land use efficiency of cassava + peanut intercropping. The yield of cassava planted in intercropping system varied from 30.26 t ha^{-1} (FYM applied yearly) to 32.47 t ha^{-1} (applied with FYM biochar).

Sokchea *et al.* (2013) conducted an experiment to measure the effect of biochar produced from rice husk and the interaction between two kinds of fertilizer (biodigester effluent and urea) on soil fertility and paddy rice grain yield in Compodia. The levels of biochar were 0 and 3 kg m^{-2} and biodigester effluent or urea was applied @ 100 kg ha^{-1} N. The rice husk biochar increased yields of rice grain and straw by 30 and 40 per cent, respectively.

Dao *et al.* (2013) carried out a study on sandy soil and feralite soil in Vietnam todeterminetheinteraction between source of biochar and soil type on growth of maize. Mixtures were made of 80 g of biochar, 2 kg of soil, 0.40 g urea, 0.20 g KCl and 0.40 g super phosphate, and put in plastic bags. Growth of maize on these soils over 35 days was increased 5.70 times by addition of 40.00 g biochar kg^{-1} of soil. The increases with biochar from coconut husks, bamboo and rice husks were 3.40, 2.50 and 2.30 times the growth on the control plot that did not receive biochar.

Rosenani *et al.* (2014) initiated experiments on leafy vegetables to determine the effects of rice husk biochar application on the yield of *Amaranthus viridis*, and *Ipomoea reptans*. Rice husk biochar applied @ 20 t ha^{-1} was able to increase the economic or fresh yield of *Amaranthus viridis* compared to the control without biochar. In *Ipomoea reptans*, the fresh yield increased significantly over the control even with the lower application rate of 15 t ha^{-1} biochar.

Widowatil and Asnah (2014) conducted a field experiment to study the effect of biochar @ 30t ha^{-1} prepared from organic waste, on K fertilizer leaching and uptake, efficiency and effectiveness of K fertilization, and economic viability of farming maize in an inceptisol. The results showed that the sole application of biochar increased maize production (6.24 t ha^{-1}) by 14 per cent compared to the sole application of KCl fertilizer (5.45 t ha^{-1}) and dual application of biochar and 75 per cent lower dosage of KCl fertilizer application increased maize production by 29.00 per cent. Application of biochar and KCl fertilizer @ 50 kg ha^{-1} resulted in the highest relative agronomic effectiveness (137.00 per cent) and K fertilizer efficiency (18.00 per cent).

Much greater yields in plant growth are observed with fertilizer additions plus biochar, as opposed to fertilizer additions alone (Asai *et al.*, 2009; Blackwell *et al.*, 2009). This apparent increase in fertilizer use efficiency with biochar is attributed to decreased bulk density, increased WHC (Chan and Xu, 2009) and the ability of biochar to retain fertilizer nutrients and reduce leaching losses (Lehmann *et al.*, 2003).

Glaser *et al.* (2002) observed that biochar @ 67 t ha^{-1} and 135 t ha^{-1} char increased biomass by 150 per cent and 200 per cent respectively in cowpea on Xanthic ferralsol. In a pot experiment, Lehmann *et al.* (2003) found biochar to increase rice biomass by 17 per cent and cowpea by 43 per cent when applied at rates of 68 to 135 t ha^{-1} C. This growth was attributed to direct nutrient additions of P, K and Cu from biochar.

Van Zwieten *et al.* (2009) assessed the effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility in a glasshouse study and reported that biochar @10 t ha^{-1} in a Ferrosol significantly increased N uptake and biomass production (250 per cent times that of control) in wheat therefore suggested improved fertilizer use efficiency. Germination of wheat in the Ferrosol was significantly improved in the presence of biochar (from 97 per cent ± 2 per cent in the control to 100 per cent).

Sika (2012) carried out a wheat pot trial using the biochar-amended soil for 12 weeks and observed that application of biochar @ 0.50 per cent (10 t ha^{-1}) and 2.50 per cent (50 t ha^{-1}) increased the biomass for the fertilized treatments by 21.00 per cent and 2.50 per cent respectively and 29.00 per cent biomass increase for unfertilized treatments. In a pot trial carried out by Chan *et al.* (2007), a significant increase in the dry matter production of radish resulted when N fertilizer was used together with biochar. The results showed that in the presence of N fertilizer, there was 95.00 to 266.00 per cent variation in yield for soils with no biochar additions, in comparison to those with the highest rate of 100 t ha^{-1}. Improved fertilizer use efficiency, referring to crops giving rise to higher yield per unit of fertilizer applied (Chan and Xu, 2009), was thus shown as a major positive attribute of the application of biochar.

Hoshi (2001) found 20 per cent increase in volume and 40 per cent increase in height of tea trees with biochar additions. Schomberg *et al.* (2012) conducted an experiment to test the benefit of biochar on soil fertility and N emissions in barley and reported that 50 t ha^{-1} of biochar was used with 100 t ha^{-1} of ammonium nitrate fertilizer, the crop yield increased by 30 per cent by improvement in NUE. Jones *et al.* (2012) concluded that application of a nutrient rich wheat straw biochar @ 20 and 40 t ha^{-1} to a calcareous loamy soil resulted in significant increase in maize yield, accompanied by increased total soil N status and agronomic NUE during a 4 month field trial.

Materials and methods

3. MATERIALS AND METHODS

An investigation was carried out at College of Agriculture, Vellayani during 2011-2014 to characterise biochar from tender coconut husk and to assess its effects on soil properties, growth and yield of yard long bean (*Vigna unguiculata* subsp. *sesquipedalis*). The experiment consisted of production and characterisation of biochar, laboratory experiments *viz.* nutrient sorption-desorption studies; carbon dioxide emission studies and field experiment. The details of the laboratory and field experiments, materials used and the methods adopted are presented in this chapter.

3. 1. CHARACTERISATION OF BIOCHAR

An experiment was conducted in Department of Soil Science and Agricultural Chemistry, College of Agriculture, Vellayani to study the physico-chemical characteristics of biochar.

Tender coconut husk was collected from the nearby areas, it was dried and the dried husk was used for production of biochar. Biochar was produced by using the fabricated biochar production unit named as 'Biochar kiln' (Plate 1). The biochar kiln was manufactured out of a metallic drum with 90 cm height and 60 cm inner diameter. It is having an inlet (30 cm diameter) to feed the dried tender coconut husk and an outlet to collect biochar after pyrolysis. At the bottom of the kiln, there are 6 holes (3 cm diameter) for the limited entry of air into the chamber in which pyrolysis occurs. There is one wire mesh (5mm), above the bottom holes for separating ash from biochar. At the top of the drum, there is one exhaust pipe for the flow of syngas from the chamber (Fig. 1).

The produced biochar was allowed to cool, crushed with a ceramic pestle, sieved through 2 mm sieve and the sieved samples were used for determining its physical and chemical characteristics.

3. 1. 1. Physical Properties

1. Specific Surface Area (SSA)

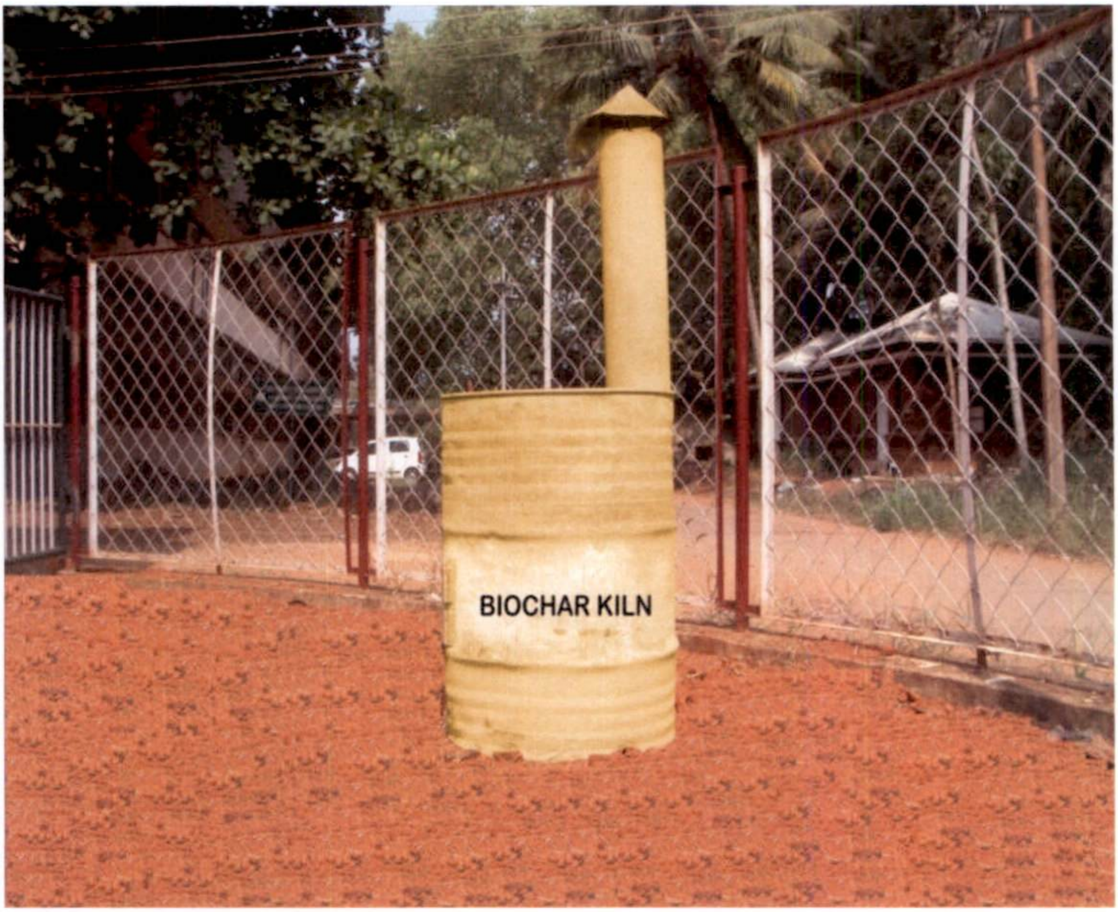


Plate 1. A view of biochar kiln for the production of tender coconut husk biochar

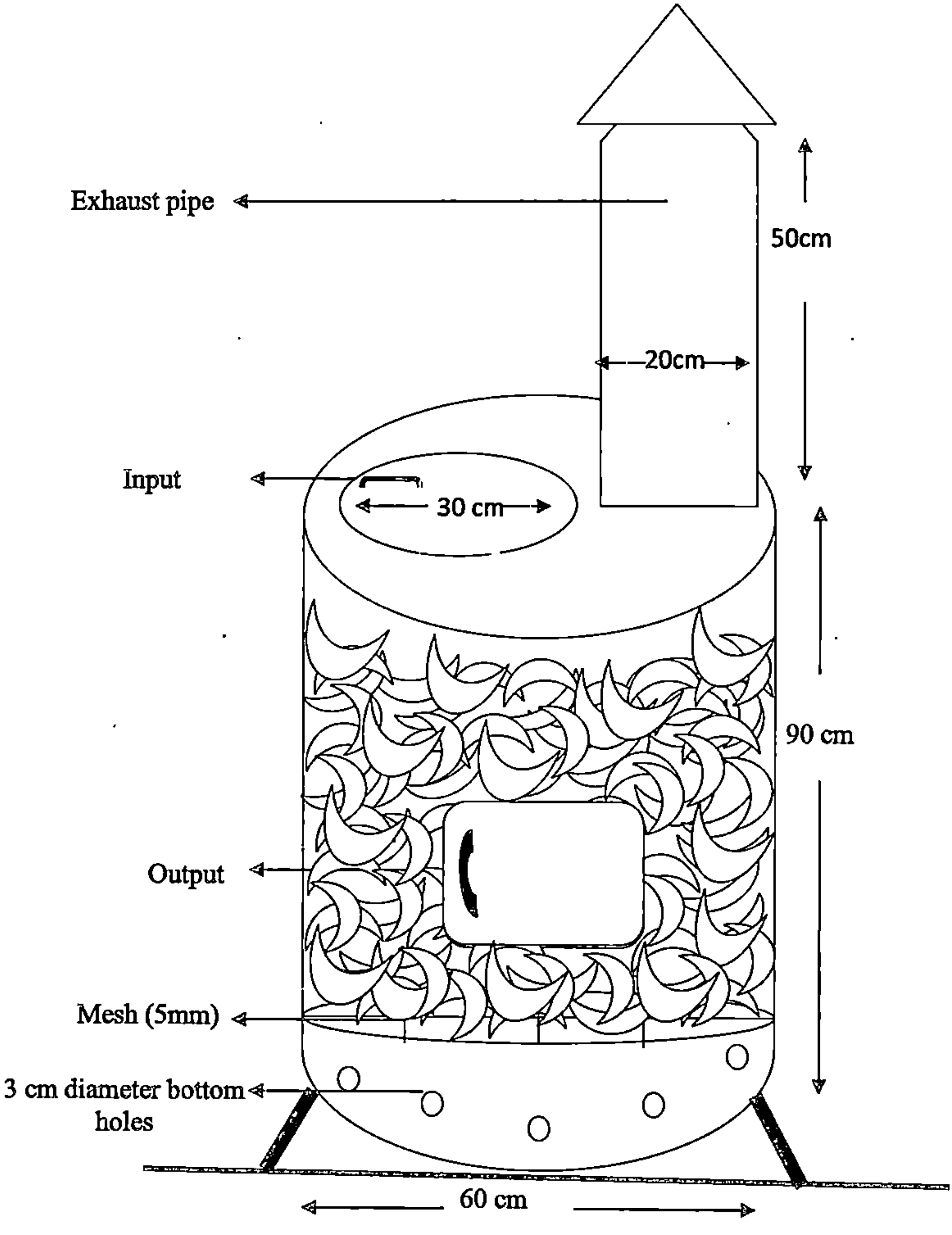


Fig. 1. Schematic diagram of biochar kiln for tender coconut husk

2. Water Holding Capacity (WHC)
3. Bulk density

3. 1. 2. Chemical Properties

1. Nutrient composition (N, P, K, Ca, Mg, S, Fe, Mn, Zn, Cu)
2. Cation Exchange Capacity (CEC)
3. pH
4. Total carbon

Analytical methods followed for the characterisation of tender coconut husk biochar are given in Table 1. pH and EC of the biochar were analysed using modified dilution of 1: 20 (biochar: de-ionised water) following the procedure suggested by Rajkovich *et al* (2011). Biochar was shaken and equilibrated with deionized-water for 1.50 hours prior to pH and EC analysis. Upon completion of the shaking and equilibration phase, pH and EC analysis were conducted on the same samples, rather than making separate replicates for pH and EC. Total C content in biochar was determined using TOC analyser by combustion at 680^{O}C and CO_2 detection by Infrared gas analyser. It was determined using loss on ignition method also.

Specific surface area of the produced biochar was determined using Surface Area Analyser by N adsorption. The detailed methodology for the determination of BET surface area, Langmuir surface area, micropore area, external surface area and micropore volume is presented in Appendix 2.

3. 2. LABORATORY EXPERIMENTS USING BIOCHAR

3. 2. 1. Nutrient Sorption- Desorption Studies using Biochar

A laboratory experiment was conducted in Department of Soil Science and Agricultural Chemistry, College of Agriculture, Vellayani to study the sorption and desorption of N, P, K, Ca, Mg, S, Fe, Mn, Zn and Cu by biochar.

4.2. 1. 1. Desorption Experiments

Desorption experiments were performed by rinsing 2 mm sieved biochar with de-ionized water which was then analysed to determine water desorbable

Table 1. Analytical methods followed for the characterisation of tender coconut husk biochar

Sl. No.	Parameter	Method	Reference
1	pH	Potentiometric method using pH meter	Jackson (1973) and Rajkovich *et al.* (2011)
2	EC	Conductometric method using EC meter	Jackson (1973) and Rajkovich *et al.* (2011)
3	Total carbon	Loss on ignition	Piper (1967)
4	CEC	Ammonium saturation using neutral normal ammonium acetate and distillation	Jackson (1973)
5	Water holding capacity	Keen Raczkowski method	Piper (1967)
6	Bulk density	Keen Raczkowski method	Piper (1967)
7	N	Microkjeldahl distillation after digestion in H_2SO_4	Jackson (1973)
8	P	Nitric–perchloric (9:4) acid digestion and colorimetry using vanado-molybdo phosphoric yellow colour method	Jackson (1973)
9	K	Nitric–perchloric (9:4) acid digestion and flame photometry	Jackson (1973)
10	Ca and Mg	Nitric–perchloric (9:4) acid digestion and versanate titration with standard EDTA	Piper (1967)
11	S	Nitric–perchloric (9:4) acid digestion and turbidimetry	Tabatabai and Bremner (1970)
12	Fe, Mn, Zn, Cu	Nitric–perchloric (9:4) acid digestion and Atomic Absorption Spectrophotometry	Jackson (1973)

nutrients. The biochar samples were taken in a container kept in a shaking incubator at 180 rpm and continuously stirred for several hours by maintaining constant temperature (25^0 C). The weight ratio of biochar to de-ionised water was 1: 100. For each rinse, the biochar suspension was stirred for 12 h, centrifuged at 10,000 rpm for 15 min and then passed through Whatman No.42 filter paper. This procedure was repeated until the pH of the filtrate stabilized between two consecutive rinses (± pH 0.02).

The pH of the rinse solutions was measured immediately after filtering and approximately 300 ml of filtrate from each rinse was stored in an airtight container at 4° C until analysed for elemental and nutrient concentrations.

After the stabilisation of pH of each rinse solution, the biochar remaining on the filter paper was rinsed into a beaker which was then placed into an oven at 105° C for several days until dry. The beakers were covered loosely with aluminum foil to reduce the risk of cross contamination.

It was assumed that the mass of biochar was conserved throughout the rinse and that all nutrient mass leached from the biochar (BC) went into solution and was measured using standard analytical methods.

$C^{i}_{final} = C_o^{i} - C^{i}_{leached}$ Where:

i = Nutrient being measured

C_{final} = Total mass of nutrient in BC at the end of a given rinse (mg kg^{-1})

C_o = Initial mass of nutrient in BC (mg kg^{-1})

$C_{leached}$ = Mass of nutrient measured in solution at the end of each rinse (mg l^{-1})

To determine the cumulative per cent of element removed, the element concentration of the rinsed BC is subtracted from the initial nutrient concentration of the BC and then divided by the initial nutrient concentration of the BC:

$$i_{desorbed}\text{ (per cent)} = \frac{C^{io}_{BC} - C^{i}_{BC}}{C^{io}_{BC}} \times 100$$

Where:

$i_{desorbed}$ (per cent) = Per cent of element (i) removed at the end of a given rinse

C^{io}_{BC} = Initial concentration of nutrient (i) in BC (mg kg^{-1})

C^{i}_{BC} = Nutrient (i) concentration in BC at the end of a given rinse (mg kg^{-1})

3.2. 1. 2. Sorption Experiments

Sorption experiments were performed in triplicate by suspending 1 g powdered biochar in a container, having 100 ml nutrient solution, containing graded doses of nutrients. The levels of nutrients were 0, 25, 50, 75 and 100 mg l^{-1} for major nutrients and 0, 12.50, 25, 37.50 and 50 mg l^{-1} for micronutrients and the sorbed nutrients were analysed. The containers were shaken at 180 rpm at 25°C and samples were drawn at 0.5, 1, 6, 12 and 24 h intervals, centrifuged at 10,000 rpm for 15 minutes and finally filtered using Whatman No.42 filter paper. The filtered samples were stored in an airtight container at 4° C until analysed for elemental and nutrient concentrations.

3.2.2. Carbon Dioxide Emission Studies

An incubation study was carried out at Department of Soil Science and Agricultural Chemistry, College of Agriculture, Vellayani to compare CO_2 emissions by application of biochar and common organic amendments namely FYM and vermicompost @ one and two percent into soil, kept at field capacity. The treatments were as follows:

T_1 Biochar @ 1 per cent
T_2 Biochar @ 2 per cent
T_3 Farmyard Manure @ 1 per cent
T_4 Farmyard Manure @ 2 per cent
T_5 Vermicompost @ 1 per cent
T_6 Vermicompost @ 2 per cent
T_7 Control (no amendments)

Design	: CRD
Treatments	: 7
Replication	: 3

CO_2 emission was estimated using the method outlined by Jenkinson and Powlson (1976), where the CO_2 evolved from the fixed quantity of incubated organic manure was collected in an alkali and quantified and expressed as mg of CO_2 evolved per 100 g soil.

3. 4. FIELD EXPERIMENT

A field experiment was carried out to investigate the efficacy of biochar from tender coconut husk for enhanced crop production, during January 2013 to April 2013, at the Instructional farm, College of Agriculture, Vellayani.

3. 4. 1. Location

The field experiment was carried out at College of Agriculture,Vellayani. The site is situated at 8^0 30 N latitude and 76^0 54 E longitude and at an altitude of 29 m above MSL.

3. 4. 2. Season

The field experiment was conducted during the period January 2013 to April 2013.

3. 4. 3. Weather

Data on weekly averages of temperature, evaporation, relative humidity and weekly totals of rainfall during the cropping period were collected from the Agro-meteorological observatory attached to the Department of Agronomy, College of Agriculture, Vellayani and are presented in Appendix I.

3. 4. 4. Soil

The soil of the experimental site belongs to the family of Loamy Skeletal Kaolinitic Isohyperthermic Rhodic Haplustult. The physical and chemical characteristics of the soil where the experiment was conducted are given in Table 2.

3. 4. 5. Materials

3. 4. 5. 1. Planting Material and Variety

Seeds of the yard long bean variety 'Vellayani Jyothika' was collected from Department of Olericulture, College of Agriculture, Vellayani. It is a long light green fruited variety, tolerent to fusarium wilt. It has been released from College of Agriculture, Vellayani and it is a selection from Sreekaryam Local.

3. 4. 5. 2. Manures and Fertilisers

Manures used were biochar, Farmyard Manure and vermicompost

Fertilisers used were Urea, Rajphos and Muriate of Potash .

Urea	46 per cent	N
Rajphos	20 per cent	P_2O_5
Muriate of Potash	60 per cent	K_2O

3. 4. 5. 3. Biofertiliser Application

The microbial consortium (PGPR mix-I) received from the Department of Microbiology, College of Agriculture, Vellayani was used for the experiment. It is the combination of different biofertilisers like *Azospirillum*, *Azotobacter* and Phosphorous Solubilising Bacteria. The consortium was applied to the plots as per treatment @ 2 per cent. AMF was also tested in field in combination with biochar @ 200 g m^2.

3. 4. 6. Design and Layout of the Experiment

3. 4. 6. 1. Field Experiment

Crop : Yard long bean

Table 2. Physico- chemical properties of the soil at the experiment site

Sl. No.	Parameter	Unit	Content
A. Mechanical composition			
1.	Coarse sand	per cent	49.15
2.	Fine sand	per cent	16.10
3.	Silt	per cent	7.25
4.	Clay	per cent	27.50
5.	Texture		Sandy clay loam
B. Physical properties			
1.	Particle density	Mg m^{-3}	2.38
2.	Bulk density	Mg m^{-3}	1.28
3.	Porosity	per cent	42.80
4.	Water Holding Capacity	per cent	27.30
5.	Water Stable Aggregates	per cent	56.70
C. Chemical properties			
1.	pH		4.80
2.	EC	dS m^{-1}	0.42
3.	CEC	cmol (+) kg^{-1}	2.56
4.	Organic C	per cent	0.76
5.	Available N	kg ha^{-1}	225.49
6.	Available P	kg ha^{-1}	75.15
7.	Available K	kg ha^{-1}	134.76
8.	Exchangeable Ca	cmol (+) kg^{-1}	1.00
9.	Exchangeable Mg	cmol (+) kg^{-1}	0.25
10.	Available S	kg ha^{-1}	17.69
11.	Available Fe	mg kg^{-1}	18.20
12.	Available Mn	mg kg^{-1}	6.50
13.	Available Zn	mg kg^{-1}	1.30
14.	Available Cu	mg kg^{-1}	0.50

Variety : Vellayani Jyothika

Design : RBD

Treatments : 9

Replication : 3

Gross plot size : 3 m x 1.8 m

Spacing : 1.50 m x 0.45 m

Treatments

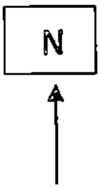
1. Recommended Dose of Fertiliser (POP, KAU)
2. Biochar @ 10 t ha^{-1} + NPK as per POP
3. Biochar @ 20 t ha^{-1} + NPK as per POP
4. Biochar @ 30 t ha^{-1} + NPK as per POP
5. Biochar @ 20 t ha^{-1} + 75 per cent NPK as per POP
6. Biochar @ 10 t ha^{-1} + FYM @ 10 t ha^{-1} +75 per cent NPK as per POP
7. Biochar @ 10 t ha^{-1} + vermicompost @ 5 t ha^{-1} + 75 per cent NPK as per POP
8. Biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP
9. Biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP

POP: FYM @ 20 t ha^{-1} + NPK @ 20: 30: 10kg ha^{-1}

3. 4. 7. Details of Cultivation

3. 4. 7. 1. Land Preparation

The experimental field was ploughed thoroughly using power tiller, clods were broken and weeds were removed. The field was laid out into 3 blocks and 27 plots (Fig. 2)



R_1	R_2	R_3
T_4	T_1	T_3
T_7	T_8	T_2
T_9	T_3	T_5
T_6	T_5	T_9
T_8	T_2	T_7
T_1	T_6	T_4
T_5	T_9	T_8
T_2	T_7	T_1
T_3	T_4	T_6

Fig. 2. Layout plan of the field experiment

3. 4. 7. 2. Manure and Fertiliser Application

The entire quantity of Farmyard Manure, Rajphos, Muriate of Potash and half the quantity of urea were applied as basal dose. Second dose of urea (25 per cent) was applied at 30 DAS and the other half (25 per cent) at 60 DAS. The entire quantity of biochar was applied 4 weeks before sowing.

3. 4. 7. 3. Sowing

Ridges and furrows were taken and seeds were dibbled at a spacing of 1.5 m between rows and 45 cm between plants for trailing on trellis. The gross number of plants per plot was 8 and the net number of plants was 4 per plot.

3. 4. 7. 4. After Cultivation

Uniform germination was observed in the field. Gap filling was done four days after sowing. The crop was thinned three weeks after emergence and the plants were allowed to trail on trellis. The crop was given regular hand weeding throughout the cropping season. Irrigation was given once in two days. Earthing up was also given along with top dressing of N. Two plants were selected randomly from the net plot area and tagged as observation plants.

3. 4. 7. 5. Plant Protection

To prevent the infestation of pod borer, Ekalux 0.20 per cent was sprayed. Copper oxychloride @ 4 g l^{-1} was drenched to manage basal rot caused by *Pythium aphanidermatum.*

3. 4. 7. 6. Harvesting

Fruits were harvested for vegetable purpose from 45-50 days after sowing. Subsequent harvests of green, immature fruits were done on alternate days from all the treatments up to 109 days after sowing and the fresh weight were recorded. After the crop period, when the vegetable yield was fallen below the economic level, the plants were pulled out, oven dried and dry weight was recorded.

3. 4. 8. Observations Recorded

3. 4. 8. 1. Biometric Observations

3. 4. 8. 1. 1. Days to First Flowering

Number of days to reach the first flowering as counted from the date of dibbling to the date in which first flowering in a plot was observed.

3. 4. 8. 1. 2. Days to Fifty Per Cent Flowering

Number of days to reach fifty per cent flowering as counted from the date of dibbling to the date in which flowering was noticed in nearly fifty per cent of the population in a plot.

3. 4. 8. 1. 3. Duration from Flowering to Final Harvest

Duration is the number of days from flowering to final harvest of the plant.

3. 4. 8. 1. 4. Vine Length

Vine length was measured from ground level to the top most leaf of the plant at 30, 60 and 90 days after dibbling and expressed in centimeters.

3. 4. 8. 1. 5. Leaves per Plant

Number of leaves produced per plant was recorded from all the observation plants and the average value was worked out.

3. 4. 8. 1. 6. Pod Length

Five pods were selected at random from the observation plants. Length of the pod was measured as the distance from pedicel attachment of the pod to the apex using twine and scale. Average was worked out and expressed in centimeters.

3. 4. 8. 1. 7. Pod Girth

The same fruits used for measuring the length were used for finding the girth. Girth was taken at the broadest part of the pod by winding a thread around it.

3. 4. 8. 1. 8. Weight of Fruits per Plant

Weight of fruits from the observation plants was recorded. Total weight of fruits from observation plants of each plot at different harvests were added and expressed as fruit yield per plant.

3. 4. 8. 1. 9. Pod Weight

Pods used for recording pod length were weighed and the average was found out and expressed in grams.

3. 4. 8. 1. 10. Number of Effective Nodules

Plants were uprooted from each plot at random without disturbing the root system and nodules were separated at fifty per cent flowering stage. The nodules with pink colour were counted to get the number of effective nodules

3. 4. 8. 1. 11. Weight of Nodules

The collected nodules were cleaned off dirt and washed with water, drained well and the weight was recorded.

3. 4. 8. 2. Yield Characters

Two representative plants selected for recording the shoot characters were used for recording yield and yield attributes.

3. 4. 8. 2. 1. Total Dry Matter Production

At harvest stage, plants were uprooted from each plot, first dried under shade and then dried in a hot air oven at 70^0 C. The total dry matter production was calculated by adding pod yield and shoots weight (oven dry basis) and expressed in kg ha^{-1}.

3. 4. 8. 2. 2. Harvest Index

Harvest Index was calculated using the formula:

$$\text{Harvest Index} = \frac{\text{Economic yield}}{\text{Biological yield}}$$

Where biological yield is the total weight of all the plant parts including pods and economic yield is the weight of pods.

3. 4. 8. 2. 3. Economic Analysis

The economics of cultivation using the treatments was worked out considering the total cost of cultivation and the prevailing market price of the produce. The benefit-cost ratio was computed as follows:

$$\text{B: C ratio} = \frac{\text{Gross Income}}{\text{Cost of cultivation}}$$

3. 9. ANALYTICAL PROCEDURES

3. 9. 1. Soil Analysis

Soil samples were taken from the experimental area before the start of the experiment, at fifty percent flowering stage and final harvest stage of the crop. The air dried samples passed through 2 mm sieve were used for the analysis of physical and chemical parameters using standard procedures as described in Table 3.

3. 9. 2. Plant Analysis

Plant samples were collected at fifty per cent flowering and at final harvest stage of the crop. The samples were oven dried at 70^0 C, powdered and used for

Table 3. Analytical methods followed in soil analysis

	Character	Method	Reference
I.	Physical properties		
	Mechanical composition	International pipette method	Piper (1967)
	Bulk density	Core sampling method	Gupta and Dakshinamurthy (1980)
	Particle density	Core sampling method	Gupta and Dakshinamurthy (1980)
	Water holding capacity	Core sampling method	Gupta and Dakshinamurthy (1980)
	Water stable aggregates	Yoder's wet sieving method	Gupta and Dakshinamurthy (1980)
II.	Chemical properties		
	pH	Potentiometric method with pH meter	Jackson (1973)
	EC	Conductometric method using EC meter	Jackson (1973)
	Organic carbon	Walkley and Black's rapid wet titration method	Walkley and Black (1934)
	CEC	Ammonium saturation using neutral normal ammonium acetate and distillation	Jackson (1973)
	Available N	Alkaline potassium permanganate method	Subbiah and Asija (1956)
	Bray No. 1 extractable P	Bray and Kurtz extraction method and ascorbic acid reduced molybdo-phosphoric blue colour method	Bray and Kurtz (1945)
	Available K	Neutral normal ammonium acetate extraction and flame photometry	Jackson (1973)
	Exchangeable Ca and Mg	Neutral normal ammonium acetate extraction and titration with EDTA	Hesse (1971)
	Available S	Extraction by $CaHPO_4$ and Turbidimetry	Chesnin and Yein (1950)
	Available Fe, Mn, Zn, Cu	Extraction by 0.1M HCl and Atomic Absorption Spectrophotometry	O'Connor (1988)

the estimation of N, P, K, Ca, Mg, S, Fe, Mn, Zn and Cu. Standard procedures adopted are given in Table 4.

3. 9. 3. Pod Analysis

Pods from the sample plants were collected, dried and powdered. Chemical analysis was carried out for the estimation of nutrient composition viz. N, P, K, Ca, Mg, S, Fe, Mn, Zn and Cu. Procedures adopted were same as that for plant analysis.

3. 9. 4. Carbon Dioxide Emission in the Field

A plastic bottle was used for this experiment. It was fixed in soil after removing the bottom portion. Glass vials containing NaOH were placed inside the bottle in order to absorb the CO_2 emitted from soil and the mouth of the bottle was closed. The glass vials were taken once in a fortnight for the estimation of CO_2 evolved and expressed as $\mu g\ m^{-2}$.

3. 10. STATISTICAL ANALYSIS

Statistical analysis of the data from field experiment was carried out using Randomized Block Design described by Cochran and Cox (1969). Sorption and desorption experimental results were statistically analysed using regression analysis described by Rangaswamy (2010).

Table 4. Analytical methods followed in plant analysis

Sl. No.	Nutrient	Method	Reference
1	N	Microkjeldahl distillation after digestion in H_2SO_4	Jackson (1973)
2	P	Nitric–perchloric (9:4) acid digestion and colorimetry using vanado-molybdo phosphoric yellow colour method	Jackson (1973)
3	K	Nitric–perchloric (9:4) acid digestion and flame photometry	Jackson (1973)
4	Ca and Mg	Nitric–perchloric (9:4) acid digestion and versanate titration with standard EDTA	Piper (1967)
5	S	Nitric–perchloric (9:4) acid digestion and turbidimetry	Tabatabai and Bremner (1970)
6	Fe, Mn, Zn, Cu	Nitric–perchloric (9:4) acid digestion and Atomic Absorption Spectrophotometry	Jackson (1973)

Results

4. RESULTS

Investigations were carried out at College of Agriculture, Vellayani to characterise biochar from tender coconut husk and to assess its effects on soil properties, growth and yield of yard long bean (*Vigna unguiculata* subsp. *sesquipedalis*). The experiment consisted of production and characterisation of biochar, laboratory experiments *viz.* nutrient sorption- desorption studies; carbon dioxide emission studies and field experiment. The results of the study are presented in this section.

4. 1. CHARACTERISATION OF BIOCHAR

Biochar was produced from tender coconut husk using the fabricated apparatus (Biochar kiln) by the process of pyrolysis at temperature of 350-400^{0}C. By the conversion of 30 kg tender coconut husk, 10 kg biochar can be produced within 1.50 h by the process of slow pyrolysis using Biochar kiln. A view of biochar production from tender coconut husk has been presented in Plate 2.

Physical and chemical properties of biochar were analysed and chemical properties were compared with that of raw material. The data is presented in Table 5 and Table 6. The biochar produced was having an alkaline pH (9.13) where as the pH of tender coconut husk was 6.32. The EC, CEC, total C , N, P, K, Ca, Mg, S, Fe, Mn, Zn and Cu contents of tender coconut husk biochar were 1.73 dS m^{-1}, 15.26 cmol kg^{-1}, 72.30 per cent, 1.05 per cent, 0.38 per cent, 2.27 per cent, 0.40 per cent, 0.29 per cent, 0.27 per cent, 123.04 mg kg^{-1}, 16.50 mg kg^{-1}, 21.09 mg kg^{-1} and 3.98 mg kg^{-1} respectively whereas tender coconut husk recorded 0.97 dS m^{-1}, 8.63 cmol kg^{-1}, 56.54 per cent, 0.85 per cent, 0.14 per cent, 1.45 per cent, 0.32 per cent, 0.20 per cent, 0.29 per cent, 105.65 mg kg^{-1}, 9.37 mg kg^{-1}, 15.08 mg kg^{-1} and 3.02 µg g^{-1} respectively. All the chemical properties except S content were higher for biochar when compared to raw tender coconut husk. Biochar recorded the C: N ratio of 68.86 whereas tender coconut husk registered the value of 66.52. C: P ratio was 190.26 and C: S ratio was 267.78 for tender coconut husk biochar, where as the raw material had C: P ratio of 403.86 and C: S ratio of

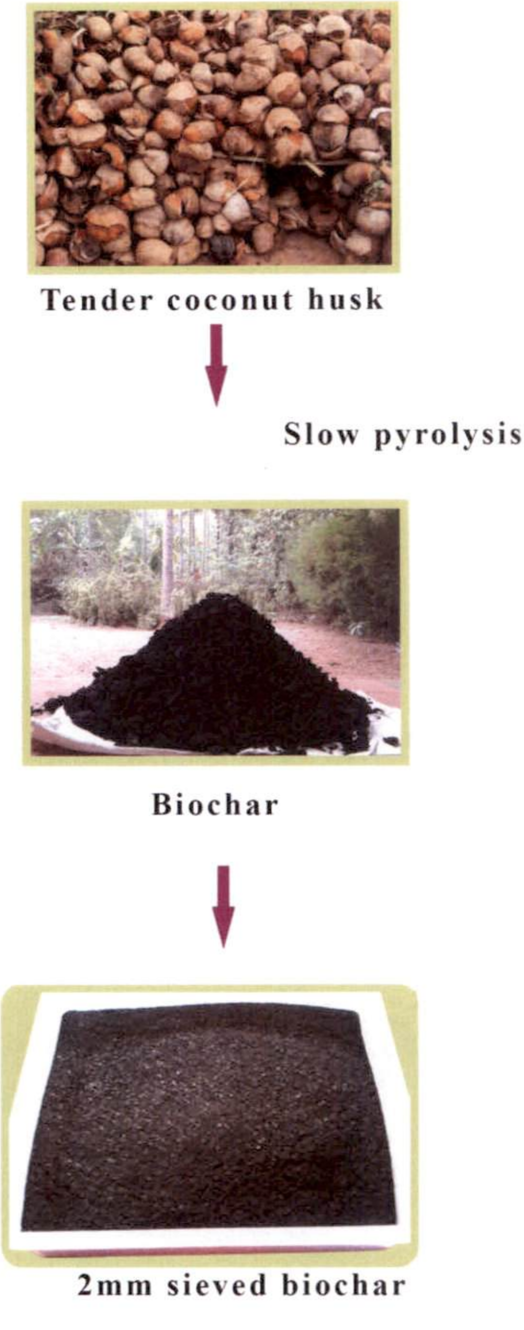


Plate 2. A view of biochar production from tender coconut husk

Table 5. Chemical properties of tender coconut husk and biochar from husk

Parameters	Units	Biochar from husk	Tender coconut husk
pH		9.13	6.32
EC	dS m^{-1}	1.73	0.97
CEC	cmol kg^{-1}	15.26	8.63
Total C	per cent	72.30	56.54
N	per cent	1.05	0.85
P	per cent	0.38	0.14
K	per cent	2.27	1.45
Ca	per cent	0.40	0.32
Mg	per cent	0.29	0.20
S	per cent	0.27	0.29
Fe	mg kg^{-1}	123.04	105.65
Mn	mg kg^{-1}	16.50	9.37
Zn	mg kg^{-1}	21.09	15.08
Cu	mg kg^{-1}	3.98	3.02
C:N		68.86	66.52
C:P		190.26	403.86
C:S		267.78	195.00
C:N:P:S		72.3: 1: 0.38: 0.27	56.54: 0.85: 0.14: 0.29

Table 6. Physical properties of tender coconut husk biochar

Parameters	Unit	Values
Water holding capacity	per cent	226.00
Bulk density	Mg m^{-3}	0.14
BET surface area	m^2 g^{-1}	157.93
Langmuir surface area	m^2 g^{-1}	237.81
Micropore area	m^2 g^{-1}	110.83
External surface area	m^2 g^{-1}	47.10
Micropore volume	m^2 g^{-1}	0.06

195.00. The produced biochar recorded WHC of 226.00 per cent, bulk density of 0.14 Mg m^{-3}, BET surface area of 157.93 m^2 g^{-1}, Langmuir surface area of 237.81 m^2 g^{-1}, micropore area of 110.83 m^2 g^{-1}, external surface area of 47.10 m^2 g^{-1} and micropore volume of 0.06 cm^3 g^{-1} (Table 6)

4.2. LABORATORY EXPERIMENTS USING BIOCHAR

Laboratory studies were conducted at Department of Soil Science and Agricultural Chemistry, College of Agriculture, Vellayani and the following results were obtained. A view of the laboratory experiments are depicted in Plate 3.

4. 2. 1. Nutrient Sorption- Desorption Studies

4.2.1.1. Desorption of Nutrients from Biochar

Desorption experiments were performed by rinsing 1 kg powdered biochar with de-ionised water in 1:100 ratio. The biochar solution was shaken for several hours and samples were drawn at 12 h interval until the pH of the filtrate was stabilised between two consecutive rinses. pH of the rinse solution was stabilised after 72 h. At 12 h after shaking, pH of the solution was 9.00. Then the pH decreased slightly after which an increase was observed. At 24, 36, 48, 60 and 72 h after shaking with de-ionised water, pH of the solution was 8.70, 8.58, 8.96, 9.35 and 9.20 respectively. At 72 h after shaking, the pH was stabilised to 9.20. The pH was stabilised after 72 h. The change between the initial and the final pH was very little (9 to 9.20). After each rinse, the concentration of nutrient in the solution phase was found to be increased that resulted in a decrease in the initial concentration of the nutrient in biochar.

4.2.1.1.1. NH_4^+

The data on desorption of NH_4^+ is presented in Table 7. The N content in biochar was 10500.00 mg kg^{-1}. When biochar was equilibrated with de-ionised water, the concentration of NH_4^+ was reduced after each rinse and after 12, 24, 36, 48, 60 and 72 h, 2.00, 18.96, 20.67, 24.08 and 28.97 per cent of the initial

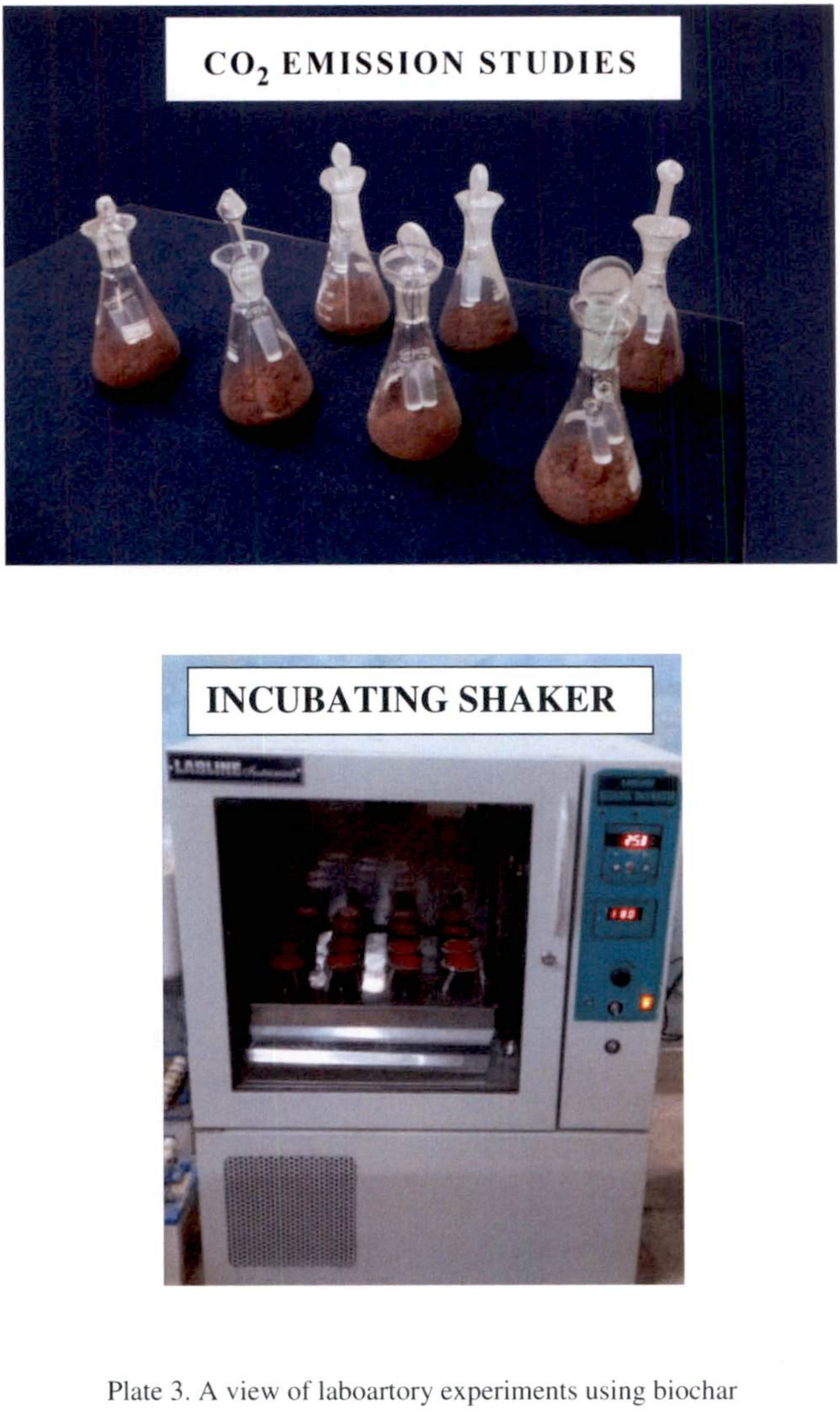


Plate 3. A view of laboartory experiments using biochar

Table 7. Desorption of NH_4^+ from biochar

Rinse number (Time)	pH of rinse solution	Initial concentration of nutrient in BC (mg kg^{-1})	Concentration of nutrient in solution at the end of each rinse (mg l^{-1})	Total concentration of nutrient in BC at the end of a given rinse (mg kg^{-1})	Cumulative per cent of element desorbed
1 (12h)	9.00	10500	210.00	10290.00	2.00
2 (24 h)	8.70	10500	1990.80	8509.20	18.96
3 (36 h)	8.58	10500	2170.35	8329.65	20.67
4 (48 h)	8.96	10500	2528.40	7971.60	24.08
5 (60 h)	9.35	10500	3041.85	7458.15	28.97
6 (72 h)	9.20	10500	3386.25	7113.75	32.25
7 (84 h)	9.20	10500	3386.25	7113.75	32.25

Table 8. Desorption of PO_4^{3-} from biochar

Rinse number (Time)	pH of rinse solution	Initial concentration of nutrient in BC (mg kg^{-1})	Concentration of nutrient in solution at the end of each rinse (mg l^{-1})	Total concentration of nutrient in BC at the end of a given rinse (mg kg^{-1})	Cumulative per cent of element desorbed
1 (12h)	9.00	3780	189.00	3591.00	5.00
2 (24 h)	8.70	3780	1053.11	2726.89	27.86
3 (36 h)	8.58	3780	1551.31	2228.69	41.04
4 (48 h)	8.96	3780	2145.53	1634.47	56.76
5 (60 h)	9.35	3780	2549.23	1230.77	67.44
6 (72 h)	9.20	3780	2858.44	921.56	75.62
7 (84 h)	9.20	3780	2859.57	920.43	75.65

concentration of NH_4^+ respectively were desorbed from biochar. A total of 32.25 per cent (3386.25 mg l^{-1}) of the initial concentration of the nutrient was found to be desorbed within 3 days, when biochar was equilibrated with de-ionised water in 1: 100 ratio. Desorption was stabilised after 72 h. Desorption of NO_3^- from biochar was nil.

4.2.1.1.2. PO_4^{3-}

The initial concentration of PO_4^{3-} in biochar was 3780 mg kg^{-1}. The desorption pattern observed was 5.00, 27.86, 41.04, 56.76, 67.44 and 75.62 per cent after 12, 24, 36, 48, 60 and 72 h respectively (Table 8). De-ionised water could release 75.62 per cent (2858.44 mg l^{-1}) of the total phosphate from biochar after 72 h of shaking using de-ionised water, in an incubating shaker maintained at 25^0C.

4.2.1.1.3. K^+

The data is presented in Table 9. The concentration of K^+ present in biochar was 22,700 mg kg^{-1}. By rinsing biochar with de-ionised water, the concentration of K^+ was observed to be decreased. 8.96, 16.28, 25.67, 32.81 and 38.32 per cent K^+ were desorbed from biochar after 12, 24, 36, 48 and 60 h respectively. Final concentration of K^+ on biochar was 12473.65 mg kg^{-1} after 3 days. At the end of 72 h of shaking, 45.05 per cent (10226.35 mg l^{-1}) of the total K^+ concentration of biochar could be released from biochar. The release was stabilised after 72 h when the pH of the rinse solution was 9.20.

4.2.1.1.4. Ca^{2+}

Initially 4000 mg of Ca^{2+} was present in one kg biochar (Table 10). The per cent desorption of Ca^{2+} from biochar was 6.20 per cent, 21.56, 32.00 and 42.00 per cent after 12, 24, 36, 48 and 60 h respectively when it was shaken using de-ionised water in 1: 100 ratio. A total of 1840 mg l^{-1} (46 per cent) Ca^{2+} was released from biochar to the solution phase after 3 days and thereafter the release was stabilised.

Table 9. Desorption of K^+ from biochar

Rinse number (Time)	pH of rinse solution	Initial concentration of nutrient in BC (mg kg^{-1})	Concentration of nutrient in solution at the end of each rinse (mg l^{-1})	Total concentration of nutrient in BC at the end of a given rinse (mg kg^{-1})	Cumulative per cent of element desorbed
1 (12h)	9.00	22700	2033.92	20666.08	8.96
2 (24 h)	8.70	22700	3695.56	19004.44	16.28
3 (36 h)	8.58	22700	5827.09	16872.91	25.67
4 (48 h)	8.96	22700	7447.87	15252.13	32.81
5 (60 h)	9.35	22700	8698.64	14001.36	38.32
6 (72 h)	9.20	22700	10226.35	12473.65	45.05
7 (84 h)	9.20	22700	10246.78	12453.22	45.14

Table 10. Desorption of Ca^{2+} from biochar

Rinse number (Time)	pH of rinse solution	Initial concentration of nutrient in BC (mg kg^{-1})	Concentration of nutrient in solution at the end of each rinse (mg l^{-1})	Total concentration of nutrient in BC at the end of a given rinse (mg kg^{-1})	Cumulative per cent of element desorbed
1 (12h)	9.00	4000	248.00	3752.00	6.20
2 (24 h)	8.70	4000	862.40	3137.60	21.56
3 (36 h)	8.58	4000	1280.00	2720.00	32.00
4 (48 h)	8.96	4000	1600.00	2400.00	40.00
5 (60 h)	9.35	4000	1680.00	2320.00	42.00
6 (72 h)	9.20	4000	1840.00	2160.00	46.00
7 (84 h)	9.20	4000	1840.00	2160.00	46.00

4.2.1.1.5. Mg^{2+}

The data regarding desorption of Mg^{2+} is presented in Table 11. The initial concentration of Mg^{2+} in biochar was 2000 mg kg^{-1}. After 12, 24, 36, 48 and 60 h, 2.07, 11.56, 14.54, 17.70 and 20.71 per cent respectively were desorbed from biochar. 23.30 per cent Mg^{2+} was desorbed from biochar to the solution phase after 72 h. Hence, rinsing of biochar with de-ionised water resulted in desorbing 676.00 mg kg^{-1} of Mg^{2+} within 3 days and thereafter it got stabilised.

4.2.1.1.6. SO_4^{2-}

The data is presented in Table 12. The initial concentration of S in biochar was 2720 mg kg^{-1}. When biochar was rinsed using de-ionised water in 1:100 ratio, there observed a decrease in the concentration of SO_4^{2-} in biochar. 5.00 per cent, 28.29 per cent, 40.18 per cent, 58.36 per cent and 69.70 per cent were released after 12, 24, 36, 48 and 60 hours respectively from biochar when it was equilibrated with de-ionised water in an incubating shaker. Biochar could desorb 74.26 per cent (2019.87 mg kg^{-1}) SO_4^{2-} to the solution phase after 72 h, after that it was stabilised.

4.2.1.1.7. Fe^{2+}

Fe^{2+} concentration in biochar was 123.04 mg kg^{-1}. It was reduced after each rinse and finally it was 77.88 mg kg^{-1} after 72 h, where the concentration of the solution was 45.28 mg l^{-1}. The data is presented in Table 13. After 12, 24, 36, 48 and 60 h, 3.12, 7.09, 12.36, 23.78 and 29.26 per cent respectively were desorbed from biochar. 36.70 per cent Fe^{2+} was released from biochar to the solution phase after 72 h which accounted for 45.16 mg l^{-1}.

4.2.1.1.8. Mn^{2+}

The data is presented in Table 14. The initial concentration of Mn^{2+} in biochar was 16.50 mg kg^{-1}. After 12, 24, 36, 48 and 60 h of shaking with de-ionised water in the ratio 1:100, it could release 3.56, 9.42, 16.73 and 20.04, 25.98 per cent respectively from biochar. The final concentration on biochar was 221.39

Table 11. Desorption of Mg^{2+} from biochar

Rinse number (Time)	pH of rinse solution	Initial concentration of nutrient in BC (mg kg^{-1})	Concentration of nutrient in solution at the end of each rinse (mg l^{-1})	Total concentration of nutrient in BC at the end of a given rinse (mg kg^{-1})	Cumulative per cent of element desorbed
1 (12h)	9.00	2900	60.00	2840.00	2.07
2 (24 h)	8.70	2900	335.20	2564.80	11.56
3 (36 h)	8.58	2900	421.60	2478.40	14.54
4 (48 h)	8.96	2900	513.40	2386.60	17.70
5 (60 h)	9.35	2900	600.60	2299.40	20.71
6 (72 h)	9.20	2900	676.00	2224.00	23.31
7 (84 h)	9.20	2900	680.00	2220.00	23.45

Table 12. Desorption of SO_4^{2-} from biochar

Rinse number (Time)	pH of rinse solution	Initial concentration of nutrient in BC (mg kg^{-1})	Concentration of nutrient in solution at the end of each rinse (mg l^{-1})	Total concentration of nutrient in BC at the end of a given rinse (mg kg^{-1})	Cumulative per cent of element desorbed
1 (12h)	9.00	2720	136.00	2584.00	5.00
2 (24 h)	8.70	2720	769.49	1950.51	28.29
3 (36 h)	8.58	2720	1092.90	1627.10	40.18
4 (48 h)	8.96	2720	1587.39	1132.61	58.36
5 (60 h)	9.35	2720	1895.84	824.16	69.70
6 (72 h)	9.20	2720	2019.87	700.13	74.26
7 (84 h)	9.20	2720	2023.14	696.86	74.38

Table 13. Desorption of Fe^{2+} from biochar

Rinse number (Time)	pH of rinse solution	Initial concentration of nutrient in BC (mg kg^{-1})	Concentration of nutrient in solution at the end of each rinse (mg l^{-1})	Total concentration of nutrient in BC at the end of a given rinse (mg kg^{-1})	Cumulative per cent of element desorbed
1 (12h)	9.00	123.04	3.84	119.20	3.12
2 (24 h)	8.70	123.04	8.72	114.32	7.09
3 (36 h)	8.58	123.04	15.21	107.83	12.36
4 (48 h)	8.96	123.04	29.56	93.78	23.78
5 (60 h)	9.35	123.04	36.00	87.04	29.26
6 (72 h)	9.20	123.04	45.16	77.88	36.70
7 (84 h)	9.20	123.04	45.28	77.76	36.80

Table 14. Desorption of Mn^{2+} from biochar

Rinse number (Time)	pH of rinse solution	Initial concentration of nutrient in BC (mg kg^{-1})	Concentration of nutrient in solution at the end of each rinse (mg l^{-1})	Total concentration of nutrient in BC at the end of a given rinse (mg kg^{-1})	Cumulative per cent of element desorbed
1 (12h)	9.00	16.5	0.59	15.91	3.56
2 (24 h)	8.70	16.5	1.55	14.95	9.42
3 (36 h)	8.58	16.5	2.76	13.74	16.73
4 (48 h)	8.96	16.5	3.31	13.19	20.04
5 (60 h)	9.35	16.5	4.29	12.21	25.98
6 (72 h)	9.20	16.5	4.96	11.54	30.05
7 (84 h)	9.20	16.5	4.98	11.52	30.20

mg kg^{-1} and it was found out that after 3 days of shaking, 4.96 mg kg^{-1} (30.05 per cent) Mn^{2+} was desorbed from biochar to the solution phase after that it was stabilised.

4.2.1.1.9. Zn^{2+}

Regarding desorption of Zn^{2+} from biochar, the concentration of Zn^{2+} present in biochar (21.09 mg kg^{-1}) was reduced after each rinse and finally it was 15.45 mg kg^{-1} after 72h. The data is presented in Table 15. After 12, 24, 36, 48 and 60 h, 3.72, 9.36, 14.73, 22.08 and 25.06 per cent respectively were desorbed from biochar. 26.67 per cent Zn^{2+}, which corresponds to 5.62 mg kg^{-1}, was desorbed from biochar to the solution phase after 72 h.

4.2.1.1.10. Cu^{2+}

The data is presented in Table 16. Initially, 3.98 mg kg^{-1} Cu^{2+} was present in biochar. After rinsing biochar with de-ionised water in 1:100 ratio, the concentration of Cu^{2+} was found to be reduced and the final concentration was 2.92 mg kg^{-1} after 72 h. After 12, 24, 36, 48 and 60 h of shaking with de-ionised water 3.63 per cent, 9.35 per cent, 14.73 per cent, 22.08 per cent and 25.06 per cent respectively were released from biochar. It was observed that biochar could desorb 1.06 mg kg^{-1} (26.67 per cent) Cu^{2+} within 3 days.

Biochar from tender coconut husk (one kg) could desorb 3386.25 mg NH_4^+, 2858.44 mg PO_4^{3-}, 10226.35 mg K+, 1840 mg Ca^{2+}, 676 mg Mg^{2+}, 2019.87 mg SO_4^{2-}, 45.16 mg Fe^{2+}, 4.98 mg Mn^{2+}, 5.62 mg Zn^{2+}, 1.06 mg Cu^{2+} within 3 days when it was equilibrated with de-ionised water in 1:100 ratio. Anions like PO_4^{3-} (75.62 per cent) and SO_4^{2-} (74.26 per cent) were desorbed at a higher rate than cations and the lowest per cent of nutrients desorbed were Zn^{2+} (26.75 per cent) and Cu^{2+} (26.67 per cent). The regression line data for desorption of nutrients are presented in Table 17.

Table 15. Desorption of Zn^{2+} from biochar

Rinse number (Time)	pH of rinse solution	Initial mass of element in BC (mg kg^{-1})	Concentration of element in solution at the end of each rinse (mg l^{-1})	Total mass of element in BC at the end of a given rinse (mg kg^{-1})	Cumulative per cent of element desorbed
1 (12h)	9.00	21.09	0.78	20.31	3.72
2 (24 h)	8.70	21.09	1.97	19.12	9.36
3 (36 h)	8.58	21.09	3.11	17.98	14.73
4 (48 h)	8.96	21.09	4.66	16.43	22.08
5 (60 h)	9.35	21.09	5.29	15.80	25.06
6 (72 h)	9.20	21.09	5.62	15.47	26.67
7 (84 h)	9.20	21.09	5.64	15.45	26.75

Table 16. Desorption of Cu^{2+} from biochar

Rinse number (Time)	pH of rinse solution	Initial concentration of nutrient in BC (mg kg^{-1})	Concentration of nutrient in solution at the end of each rinse (mg l^{-1})	Total concentration of nutrient in BC at the end of a given rinse (mg kg^{-1})	Cumulative per cent of element desorbed
1 (12h)	9.00	3.98	0.14	3.84	3.63
2 (24 h)	8.70	3.98	0.37	3.61	9.35
3 (36 h)	8.58	3.98	0.59	3.39	14.73
4 (48 h)	8.96	3.98	0.88	3.10	22.08
5 (60 h)	9.35	3.98	1.00	2.98	25.06
6 (72 h)	9.20	3.98	1.06	2.92	26.67
7 (84 h)	9.20	3.98	1.06	2.92	26.72

Table 17. Regression line data for desorption of nutrients from biochar

Nutrient	Regression equation	R^2
NH_4^+	$C=503.25 + 39.26^{**}t$ (5.14)	0.84
PO_4^{3-}	$C=83.70 + 37.56^{**}t$ (8.45)	0.93
K^+	$C=1086.36 + 120.75^{**}t$ (11.80)	0.97
Ca^{2+}	$C=317.03 + 21.22^{**}t$ (5.58)	0.86
Mg^{2+}	$C=80.89 + 8.10^{**}t$ (6.67)	0.90
SO_4^{2-}	$C=79.93 + 26.68^{**}t$ (7.40)	0.92
Fe^{2+}	$C=-4.89 + 0.65^{**}t$ (11.89)	0.97
Mn^{2+}	$C=-0.13+0.06^{**}t$ (11.24)	0.96
Zn^{2+}	$C=0.43+ 0.07^{**}t$ (7.38)	0.92
Cu^{2+}	$C=0.08+ 0.01^{**}t$ (7.21)	0.91

C-Quantity of nutrient desorbed at t

t- Time in hours

Values in the parenthesis are table values to test the significance

**- Coefficient is significant at 1 per cent level

4. 2. 1.2. Sorption Experiments

Sorption experiments were performed on rinsed, pH stabilised biochar in triplicate by suspending 1 kg powdered biochar in container, having 100ml nutrient solution, containing graded doses of nutrients. The levels of nutrients were 25, 50, 75 and 100 mg l^{-1} for major nutrients and 12.50, 25, 37.50 and 50 mg l^{-1} for micronutrients and sorbed nutrients were analysed. The containers with biochar and nutrient solutions were shaken at 180 rpm at 25°C and samples were drawn at 0.5, 1, 6, 12 and 24 h intervals, centrifuged at 10,000 rpm for 15 min and finally filtered using Whatman No.42 filter paper.

4. 2. 1. 2. 1. NH_4^+

The data is presented in Table 18. It was observed that as the time progresses, sorption of NH_4^+ also increased. When biochar was equilibrated with 25 mg l^{-1} N for half an hour, 1, 6, 12 and 24 h, 100 per cent sorption was observed at all the time intervals.

When nutrient solution containing 50 mg l^{-1} N was used for shaking with biochar for half an hour and one hour, the per cent nutrient sorbed on biochar were 59.00 and 62.00 per cent respectively. The per cent sorption was 100 when biochar was equilibrated for 6, 12 and 24 h.

After equilibrating biochar with solution containing 75 mg l^{-1} N, 25.00, 31.00, 62.67, 100 and 100 per cent of the nutrient provided was found to be sorbed on biochar within half an hour, 1, 6, 12 and 24 h respectively.

When biochar was equilibrated with 100 mg l^{-1} solution containing N for different time intervals, 16.00 per cent of the nutrient was sorbed within half an hour. Within 1, 6, 12 and 24 h, 28.00, 44.00, 72.00 and 100 per cent respectively were sorbed on biochar.

Table 18. Sorption of NH_4^+ on biochar

Time (t)	Concentration of nutrient solution (mg l^{-1})	Concentration of the nutrient in solution at t (mg l^{-1})	Quantity of nutrient adsorbed, x/m (mg kg^{-1})	Per cent of nutrient adsorbed
½ h	25	0.00	25.0	100
	50	20.50	29.50	59
	75	56.25	18.75	25
	100	84.00	16.00	16
1 h	25	0.00	25.00	100
	50	19.00	31.00	62
	75	51.75	23.25	31
	100	72.00	28.00	28
6 h	25	0.00	25.00	100
	50	0.00	50.00	100
	75	28.00	47.00	62.67
	100	56.00	44.00	44
12 h	25	0.00	25.00	100
	50	0.00	50.00	100
	75	0.00	75.00	100
	100	28.00	72.00	72
24 h	25	0.00	25.00	100
	50	0.00	50.00	100
	75	0.00	75.00	100
	100	0.00	100.00	100

It can be concluded that after 24 h of equilibration, at all the four levels of the nutrient provided, 100 per cent of the NH_4^+-N was sorbed and it took one day for the full adsorption of 100 mg l^{-1} of NH_4^+-N from the nutrient solution.

4. 2. 1. 2. 2. PO_4^{3-}

When biochar was equilibrated with 25. mg l^{-1} solution containing PO_4^{3-}, 8.10, 35.92, 62.55, 84.29 and 96.67 per cent PO_4^{3-} were sorbed on biochar at half an hour, 1, 6, 12 and 24 h respectively (Table 19).

The per cent of PO_4^{3-} adsorbed were 9.36, 33.48, 64.16, 82.68 and 99.78 per cent, when biochar was equilibrated with 50 mg l^{-1} PO_4^{3-} solution for half an hour, 1, 6, 12 and 24 h respectively.

After equilibrating biochar with solution containing 75 mg l^{-1} PO_4^{3-}, 10.30 per cent , 30.43 per cent, 61.76 per cent, 82.42 per cent and 96.14 per cent of the nutrient provided was found to be sorbed on biochar within half an hour, 1 h, 6 h, 12 h and 24 h respectively.

When nutrient solution containing 100 mg l^{-1} PO_4^{3-} was used for shaking with biochar for half an hour, 1, 6, 12 and 24 h, the per cent nutrient sorbed on biochar were 9.76, 33.17, 65.48, 83.06 and 90.70 mg kg^{-1} respectively. It was observed that as the equilibrating time increased, the sorption also increased.

4. 2.1. 2. 3. K^+

The data is presented in Table 20. The sorption of K^+ was 8.00, 24.00, 44.00, 64.00 and 100 per cent, when biochar was shaken with 25 mg l^{-1} K^+ for half an hour, 1, 6, 12 and 24 h respectively.

When nutrient solution containing 50 mg l^{-1} K^+ was used for shaking with biochar for half an hour, 1,6, 12 and 24 h, the per cent nutrient sorbed on biochar were 10.00, 24.00, 42.00, 64.00 and 100 per cent respectively.

Table 19. Sorption of PO_4^{3-} on biochar

Time (t)	Concentration of nutrient solution (mg l^{-1})	Concentration of the nutrient in solution at t (mg l^{-1})	Quantity of nutrient adsorbed, x/m (mg kg^{-1})	Per cent of nutrient adsorbed
½ h	25	22.97	2.03	8.10
	50	45.32	4.68	9.36
	75	67.28	7.73	10.30
	100	90.24	9.76	9.76
1 h	25	16.02	8.98	35.92
	50	33.26	16.74	33.48
	75	52.18	22.82	30.43
	100	66.83	33.16	33.17
6 h	25	9.36	15.64	62.55
	50	17.92	32.08	64.16
	75	28.68	46.32	61.76
	100	34.52	65.48	65.48
12 h	25	3.93	21.07	84.29
	50	8.66	41.34	82.68
	75	13.19	61.81	82.42
	100	16.94	83.06	83.06
24 h	25	0.83	24.17	96.67
	50	0.11	49.89	99.78
	75	2.89	72.11	96.14
	100	9.30	90.70	90.70

Table 20. Sorption of K^+ on biochar

Time (t)	Concentration of nutrient solution (mg l^{-1})	Concentration of the nutrient in solution at t (mg l^{-1})	Quantity of nutrient adsorbed, x/m (mg kg^{-1})	Per cent of nutrient adsorbed
½ h	25	23	2	8.00
	50	45	5	10.00
	75	69	6	8.00
	100	92	8	8.00
1 h	25	19	6	24.00
	50	38	12	24.00
	75	57	18	24.00
	100	76	24	24.00
6 h	25	14	11	44.00
	50	29	21	42.00
	75	27	48	64.00
	100	36	64	64.00
12 h	25	9	16	64.00
	50	18	32	64.00
	75	13	62	82.67
	100	22	78	78.00
24 h	25	0	25	100.00
	50	0	50	100.00
	75	2	73	97.33
	100	8	92	92.00

After equilibrating biochar with solution containing 75 mg l^{-1} K^+, 8.00, 24.00, 64.00, 82.67 and 97.33 per cent of the nutrient provided was found to be sorbed on biochar within half an hour, 1, 6, 12 and 24 h respectively.

When biochar was equilibrated with 100 mg l^{-1} solution containing K^+, for different time intervals viz. half an hour, 1, 6, 12 and 24 h, 8.00, 24.00, 64.00, 78.00 and 92.00 mg kg^{-1} K^+ respectively were sorbed on biochar. 1 kg could sorb about 92 mg of K^+ in 24 h of equilibration. It was observed that as the time progressed, adsorption of K^+ also increased.

4.2.1.2. 4. Ca^{2+}

The data is presented in Table 21. After equilibrating biochar with solution containing 25 mg l^{-1} Ca^{2+}, 12.56, 30.92, 49.44, 60.20 and 94.80 per cent of the nutrient provided was found to be sorbed on biochar within half an hour, 1, 6, 12 and 24 h respectively.

When biochar was equilibrated with 50 mg l^{-1} solution containing Ca^{2+}, for different time intervals viz. half an hour, 1, 6, 12 and 24 h, 10.84, 25.24, 42.12, 66.56 and 96.42 per cent PO_4^{3-} respectively were sorbed on biochar.

The sorption of Ca^{2+} was 9.57, 25.41, 65.84, 84.49 and 88.61 per cent, when biochar was shaken with 75mg l^{-1} for half an hour, 1, 6, 12 and 24 h respectively.

When nutrient solution containing 100 mg l^{-1} Ca^{2+} was used for shaking with biochar for half an hour, 1, 6, 12 and 24 h, the per cent nutrient sorbed on biochar were 10.06, 25.58, 64.16, 79.72 and 87 mg kg^{-1} respectively.

During the course of time, the per cent of nutrient adsorption increases.

Table 21. Sorption of Ca^{2+} on biochar

Time (t)	Concentration of nutrient solution (mg l^{-1})	Concentration of the nutrient in solution at t (mg l^{-1})	Quantity of nutrient adsorbed, x/m (mg kg^{-1})	Per cent of nutrient adsorbed
½ h	25	21.86	3.14	12.56
	50	44.58	5.42	10.84
	75	67.82	7.18	9.57
	100	89.94	10.06	10.06
1 h	25	17.27	7.73	30.92
	50	37.38	12.62	25.24
	75	55.94	19.06	25.41
	100	74.42	25.58	25.58
6 h	25	12.64	12.36	49.44
	50	28.94	21.06	42.12
	75	25.62	49.38	65.84
	100	35.84	64.16	64.16
12 h	25	9.95	15.05	60.20
	50	16.72	33.28	66.56
	75	11.63	63.37	84.49
	100	20.28	79.72	79.72
24 h	25	1.30	23.70	94.80
	50	1.79	48.21	96.42
	75	8.54	66.46	88.61
	100	13.00	87.00	87.00

4.1.2. 5. Mg^{2+}

The data is presented in Table 22. When biochar was equilibrated with 25 mg l^{-1} solution containing Mg^{2+}, for different time intervals *viz.* half an hour, 1, 6, 12 and 24 h, 8.44, 26.08, 49.88, 66.92 and 100 per cent Mg^{2+} respectively were sorbed on biochar.

The per cent of Mg^{2+} sorption was 8.10, 23.46, 43.38, 64.42 and 98.32, when biochar was shaken with 50 mg l^{-1} for half an hour, 1, 6, 12 and 24 h respectively.

After equilibrating biochar with solution containing 75 mg l^{-1} Mg^{2+}, 8.75, 24.20, 63.04, 83.16 and 88.43 per cent of the nutrient provided was found to be sorbed on biochar within half an hour, 1, 6, 12 and 24 h respectively.

When nutrient solution containing 100 mg l^{-1} Mg^{2+} was used for shaking with biochar for half an hour, 1, 6, 12 and 24 h, 9.19, 24.38, 65.72, 78.62 and 86.15 mg kg^{-1} of Mg^{2+} respectively were sorbed on biochar.

4. 2. 1. 2. 6. SO_4^{2-}

The data is presented in Table 23. It was observed that as the time progresses, adsorption of SO_4^{2-} also increases. 13.91, 41.53, 62.15, 90.82 and 99.49 per cent sorption of SO_4^{2-} was observed when biochar was shaken with 25 mg l^{-1} for half an hour, 1, 6, 12 and 24 h respectively.

When nutrient solution containing 50 mg l^{-1} SO_4^{2-} was used for shaking with biochar for half an hour, 1, 6, 12 and 24 h, the per cent nutrient sorbed on biochar were 12.57, 39.41, 64.70, 87.36 and 98.15 per cent respectively.

After equilibrating biochar with solution containing 75 mg l^{-1} SO_4^{2-}, 12.08, 37.71, 61.64, 87.37 and 99.17 per cent of the nutrient provided was found to be sorbed on biochar within half an hour, 1, 6, 12 and 24 h respectively.

Table 22. Sorption of Mg^{2+} on biochar

Time (t)	Concentration of nutrient solution (mg l^{-1})	Concentration of the nutrient in solution at t (mg l^{-1})	Quantity of nutrient adsorbed, x/m (mg kg^{-1})	Per cent of nutrient adsorbed
½ h	25	22.89	2.11	8.44
	50	45.95	4.05	8.10
	75	68.44	6.56	8.75
	100	90.81	9.19	9.19
1 h	25	18.48	6.52	26.08
	50	38.27	11.73	23.46
	75	56.85	18.15	24.20
	100	75.62	24.38	24.38
6 h	25	12.53	12.47	49.88
	50	28.31	21.69	43.38
	75	27.72	47.28	63.04
	100	34.28	65.72	65.72
12 h	25	8.27	16.73	66.92
	50	17.79	32.21	64.42
	75	12.63	62.37	83.16
	100	21.38	78.62	78.62
24 h	25	0.00	25.00	100.00
	50	0.84	49.16	98.32
	75	8.68	66.32	88.43
	100	13.85	86.15	86.15

Table 23. Sorption of SO_4^{2-} on biochar

Time (t)	Concentration of nutrient solution (mg l^{-1})	Concentration of the nutrient in solution at t (mg l^{-1})	Quantity of nutrient adsorbed, x/m (mg kg^{-1})	Per cent of nutrient adsorbed
½ h	25	21.52	3.48	13.91
	50	43.72	6.29	12.57
	75	65.94	9.06	12.08
	100	86.32	13.68	13.68
1 h	25	14.62	10.38	41.53
	50	30.30	19.70	39.41
	75	46.71	28.29	37.71
	100	60.52	39.48	39.48
6 h	25	9.46	15.54	62.15
	50	17.65	32.35	64.70
	75	28.77	46.23	61.64
	100	33.21	66.79	66.79
12 h	25	2.30	22.70	90.82
	50	6.32	43.68	87.36
	75	9.47	65.53	87.37
	100	14.04	85.96	85.96
24 h	25	0.13	24.87	99.49
	50	0.93	49.08	98.15
	75	0.62	74.38	99.17
	100	8.18	91.82	91.82

When biochar was equilibrated with 100 mg l^{-1} solution containing SO_4^{2-}, for different time intervals *viz.* half an hour, 1, 6, 12 and 24 h, 13.68, 39.48, 66.79, 85.96 and 91.92 mg kg^{-1} SO_4^{2-} respectively were sorbed on biochar.

4. 2. 1. 2. 7. Fe^{2+}

The data is presented in Table 24. During the course of time, the per cent of nutrient adsorption increased. After equilibrating biochar with solution containing 12.50 mg l^{-1} Fe^{2+}, 5.80, 28.20, 50.52, 99.56 and 100 per cent of the nutrient provided was found to be sorbed on biochar within half an hour, 1, 6, 12 and 24 h respectively.

When biochar was equilibrated with 25 mg l^{-1} solution containing Fe^{2+}, for different time intervals *viz.* half an hour, 1, 6, 12 and 24 h, 7.56, 25.04, 43.70, 99.18 and 100 per cent Fe^{2+} respectively were sorbed on biochar.

Regarding the sorption of Fe^{2+} on biochar, 8.59, 26.23, 66.65, 99.40 and 99.97 per cent sorption of Fe^{2+} was found to be sorbrd when it was shaken with 37.50 mg l^{-1} solution containing Fe^{2+} for half an hour, 1, 6, 12 and 24 h respectively.

When nutrient solution containing 50 mg l^{-1} Fe^{2+} was used for shaking with biochar for half an hour, 1, 6, 12 and 24 h, the amount of nutrient sorbed on biochar were 4.93, 12.69, 32.17, 49.50 and 49.84 mg kg^{-1} respectively. Within 24 h, one kg biochar could sorb about 50 mg of Fe^{2+}.

4. 2. 1. 2. 8. Mn^{2+}

The data is presented in Table 25. When biochar was equilibrated with 12.50 mg l^{-1} solution containing Mn^{2+}, for different time intervals *viz.* half an hour, 1, 6, 12 and 24 h, 29.44, 53.80, 82.52, 99.44 and 100 per cent Mn^{2+} respectively were sorbed on biochar.

Table 24. Sorption of Fe^{2+} on biochar

Time (t)	Concentration of nutrient solution (mg l^{-1})	Concentration of the nutrient in solution at t (mg l^{-1})	Quantity of nutrient adsorbed, x/m (mg kg^{-1})	Per cent of nutrient adsorbed
½ h	12.5	11.78	0.73	5.80
	25.0	23.11	1.89	7.56
	37.5	34.28	3.22	8.59
	50.0	45.07	4.93	9.86
1 h	12.5	8.98	3.53	28.20
	25.0	18.74	6.26	25.04
	37.5	27.67	9.84	26.23
	50.0	37.31	12.69	25.38
6 h	12.5	6.19	6.32	50.52
	25.0	14.08	10.93	43.70
	37.5	12.51	25.00	66.65
	50.0	17.84	32.17	64.33
12 h	12.5	0.06	12.45	99.56
	25.0	0.21	24.80	99.18
	37.5	0.23	37.28	99.40
	50.0	0.51	49.50	98.99
24 h	12.5	0.00	12.50	100.00
	25.0	0.00	25.00	100.00
	37.5	0.01	37.49	99.97
	50.0	0.17	49.84	99.67

Table 25. Sorption of Mn^{2+} on biochar

Time (t)	Concentration of nutrient solution (mg l^{-1})	Concentration of the nutrient in solution at t (mg l^{-1})	Quantity of nutrient adsorbed, x/m (mg kg^{-1})	Per cent of nutrient adsorbed
½ h	12.5	8.82	3.68	29.44
	25.0	17.98	7.03	28.10
	37.5	26.17	11.34	30.23
	50.0	37.26	12.75	25.49
1 h	12.5	5.78	6.73	53.80
	25.0	11.37	13.64	54.54
	37.5	21.43	16.07	42.85
	50.0	20.67	29.33	58.66
6 h	12.5	2.19	10.32	82.52
	25.0	5.46	19.54	78.16
	37.5	7.12	30.39	81.03
	50.0	10.31	39.69	79.38
12 h	12.5	0.07	12.43	99.44
	25.0	0.38	24.63	98.50
	37.5	0.60	36.90	98.40
	50.0	1.79	48.22	96.43
24 h	12.5	0.00	12.50	100.00
	25.0	0.00	25.00	100.00
	37.5	0.00	37.50	100.00
	50.0	0.00	50.00	100.00

28.10, 54.54, 78.16, 98.50 and 100 per cent adsorption of Mn^{2+} was observed when biochar was shaken with 25 mg l^{-1} for half an hour, 1, 6, 12 and 24 h respectively.

After equilibrating biochar with solution containing 37.50 mg l^{-1} Mn^{2+}, 30.23, 42.85, 81.03 and 98.40 and 100 per cent of the nutrient provided was found to be sorbed on biochar within half an hour, 1, 6, 12 and 24 h respectively.

When nutrient solution containing 50 mg l^{-1} Mn^{2+} was used for shaking with biochar for half an hour, 1, 6, 12 and 24 h, the per cent nutrient sorbed on biochar were 25.49, 58.66, 79.38, 96.43 and 100 respectively.

4. 2. 1. 2. 9. Zn^{2+}

The data is presented in Table 26. 23.84, 62.24, 94.24, 99.40 and 100 per cent sorption of Zn^{2+} was observed when biochar was shaken with 12.50 mg l^{-1} for half an hour, 1, 6, 12 and 24 h respectively.

When nutrient solution containing 25 mg l^{-1} Zn^{2+} was used for shaking with biochar for half an hour, 1, 6, 12 and 24 h, the per cent nutrient sorbed on biochar were 20.10, 63.48, 85.62, 98.74 and 100 respectively.

After equilibrating biochar with solution containing 37.50 mg l^{-1} Zn^{2+}, 21.19, 61.69, 88.05, 99.49 and 99.11 per cent of the nutrient provided was found to be sorbed on biochar within half an hour, 1, 6, 12 and 24 h respectively.

When biochar was equilibrated with 50 mg l^{-1} solution containing Zn^{2+}, for different time intervals viz. half an hour, 1, 6, 12 and 24 h, 23.55, 64.66, 85.48, 98.83 and 99.12 per cent SO_4^{2-} respectively were sorbed on biochar. About 50 mg of Zn^{2+} could be sorbed by one kg of biochar in 24 h.

Table 26. Sorption of Zn^{2+} on biochar

Time (t)	Concentration of nutrient solution ($mg\ l^{-1}$)	Concentration of the nutrient in solution at t ($mg\ l^{-1}$)	Quantity of nutrient adsorbed, x/m ($mg\ kg^{-1}$)	Per cent of nutrient adsorbed
½ h	12.5	9.52	2.98	23.84
	25.0	19.98	5.03	20.10
	37.5	29.56	7.95	21.19
	50.0	38.23	11.78	23.55
1 h	12.5	4.72	7.78	62.24
	25.0	9.13	15.87	63.48
	37.5	14.37	23.14	61.69
	50.0	17.67	32.33	64.66
6 h	12.5	0.72	11.78	94.24
	25.0	3.60	21.41	85.62
	37.5	4.48	33.02	88.05
	50.0	7.26	42.74	85.48
12 h	12.5	0.08	12.43	99.40
	25.0	0.32	24.69	98.74
	37.5	0.19	37.31	99.49
	50.0	0.59	49.42	98.83
24 h	12.5	0.00	12.50	100.00
	25.0	0.00	25.00	100.00
	37.5	0.34	37.17	99.11
	50.0	0.44	49.56	99.12

4. 2. 1. 2. 10. Cu^{2+}

The data is presented in Table 27. It was observed that as the time progresses, adsorption of Cu^{2+} also increases. After equilibrating biochar with solution containing 12.50 mg l^{-1} Cu^{2+}, 24.24, 69.84 , 97.08, 100 and 100 per cent of the nutrient provided was found to be sorbed on biochar within half an hour, 1, 6, 12 and 24 h respectively.

The per cent of Cu^{2+} sorption was 25.08, 71.26, 86.08, 99 and 100 sorption of Cu^{2+}, when biochar was shaken with 25mg l^{-1} for half an hour, 1, 6, 12 and 24 h respectively.

When nutrient solution containing 37.50 mg l^{-1} Cu^{2+} was used for shaking with biochar for half an hour, 1 h, 6 h, 12 h and 24 h, the per cent nutrient sorbed on biochar were 24.45, 68.51, 89.72, 99.80 and 99.12 per cent respectively.

When biochar was equilibrated with 50 mg l^{-1} solution containing Cu^{2+}, for different time intervals *viz.* half an h, 1 h, 6 h, 12 h and 24 h, 26.02, 72.42, 86.74, 99.64 and 99.12 per cent Cu^{2+} respectively were sorbed on biochar. Regression line data for sorption of nutrients is given in Table 28, Table 29 and Table 30.

4.2.2. Carbon Dioxide Emission Studies

The data is presented in Table 31. The investigation on CO_2 emission was carried out to estimate and study the amount and pattern of CO_2 emission by the application of biochar into soil and it was compared with that of common organic amendments namely FYM and vermicompost. The experiment consisted of 7 treatments with 3 replications and the treatments were biochar @ 1 per cent, biochar @ 2 per cent, FYM @ 1 per cent, FYM @ 2 per cent, vermicompost @ 1 per cent, vermicompost @ 2 per cent and control (no ammendments). CO_2 emission was monitored at fortnightly intervals for a period of 6 months.

Table 27. Sorption of Cu^{2+} on biochar

Time (t)	Concentration of nutrient solution (mg l^{-1})	Concentration of the nutrient in solution at t (mg l^{-1})	Quantity of nutrient adsorbed, x/m (mg kg^{-1})	Per cent of nutrient adsorbed
½ h	12.5	9.47	3.03	24.24
	25.0	18.73	6.27	25.08
	37.5	28.33	9.17	24.45
	50.0	36.99	13.01	26.02
1 h	12.5	3.77	8.73	69.84
	25.0	7.19	17.82	71.26
	37.5	11.81	25.69	68.51
	50.0	13.79	36.21	72.42
6 h	12.5	0.37	12.14	97.08
	25.0	3.48	21.52	86.08
	37.5	3.86	33.65	89.72
	50.0	6.63	43.37	86.74
12 h	12.5	0.00	12.50	100.00
	25.0	0.25	24.75	99.00
	37.5	0.08	37.43	99.80
	50.0	0.18	49.82	99.64
24 h	12.5	0.00	12.50	100.00
	25.0	0.00	25.00	100.00
	37.5	0.34	37.17	99.12
	50.0	0.44	49.56	99.12

Table 28. Regression line data for sorption of N, P and K on biochar

Concentration (mg kg^{-1})	Regression equation	R^2
NH_4^+		
50	C=34.88 + 0.83 t (1.94)	0.56
75	C=26.32 + 2.47**t (3.35)	0.79
100	C=22.10+3.44**t (9.03)	0.96
PO_4^{3-}		
25	C=7.23+0.82**t (3.36)	0.79
50	C=14.11+1.70**t (3.72)	0.82
75	C=20.50+2.49**t (3.71)	0.82
100	C=30.03+3.03 t (2.96)	0.74
K^+		
25	C=4.12+0.91**t (9.03)	0.96
50	C=8.37+1.80**t (10.79)	0.97
75	C=18.34+2.65**t (3.63)	0.81
100	C=24.68+3.28**t (3.39)	0.79

C-Quantity of nutrient desorbed at t

t- Time in hours

Values in the parenthesis are table values to test the significance

**- Coefficient is significant at 1 per cent level

Table 29. Regression line data for sorption of Ca, Mg and S on biochar

Concentration (mg kg^{-1})	Regression equation	R^2
Ca^{2+}		
25	C=5.65+0.78**t (6.83)	0.94
50	C=9.21+1.71**t (8.73)	0.96
75	C=20.72+2.34 t (2.85)	0.73
100	C=27.09+3.01 t (3.00)	0.75
Mg^{2+}		
25	C=4.84+0.89**t (6.90)	0.94
50	C=8.23+1.79**t (8.83)	0.96
75	C=19.48 + 2.37*t (3.01)	0.75
100	C=26.70+3.00t (2.87)	0.73
SO$_4^{2-}$		
25	C=8.38+0.81**t (3.37)	0.79
50	C=16.34+1.60**t (3.33)	0.79
75	C=23.17+2.47**t (3.60)	0.81
100	C=34.47+2.88t (2.87)	0.73

C-Quantity of nutrient desorbed at t

t- Time in hours

Values in the parenthesis are table values to test the significance

**- Coefficient is significant at 1 per cent level

Table 30. Regression line data for sorption of Fe, Mn, Zn and Cu on biochar

Concentration ($\mu g\ g^{-1}$)	Regression equation	R^2
Fe^{2+}		
12.50	C=2.93+0.48**t (3.29)	0.78
25.00	C=5.26+ 0.98**t (3.49)	0.80
37.50	C=10.46+1.39*t (2.98)	0.75
50	C=13.73+1.85*t (3.08)	0.76
Mn^{2+}		
12.50	C=6.32+0.32 t (2.46)	0.67
25.00	C=12.26+0.66 t (2.61)	0.69
37.50	C=17.32+1.04 t (2.73)	0.71
50	C=24.82+1.28 t (2.42)	0.66
Zn^{2+}		
12.50	C=6.83+0.30 t (1.81)	0.52
25.00	C=12.82+0.64 t (1.96)	0.56
37.50	C=19.46+0.95 t (1.91)	0.55
50	C=26.59+1.22 t (1.95)	0.56
Cu^{2+}		
12.50	C=7.31+0.28 t (1.59)	0.46
25.00	C=14.08+0.57 t (1.81)	0.52
37.50	C=21.08+0.87 t (1.75)	0.50
50	C=12.43+1.11 t (1.74)	0.50

C-Quantity of nutrient desorbed at t, t- Time in hours

Values in the parenthesis are table values to test the significance

**- Coefficient is significant at 1 per cent level

Table 31. Effect of treatments on carbon dioxide emission at fortnightly intervals, mg CO_2 100 g^{-1} soil

Treatments	1st fortnight	2nd fortnight	3rd fortnight	4th fortnight	5th fortnight	6th fortnight
T_1	8.67	8.36	8.15	7.84	7.63	7.46
T_2	15.36	15.27	14.53	13.67	12.78	12.09
T_3	92.84	76.45	63.37	49.28	37.84	26.08
T_4	140.76	135.64	127.26	117.83	105.38	92.8
T_5	27.32	24.85	21.96	14.53	10.97	8.56
T_6	44.67	37.16	29.05	21.48	16.80	11.56
T_7	5.63	5.49	5.36	5.18	5.03	4.96
CD (0.05)	1.130	1.065	0.815	0.506	0.831	0.323

Table 31. Effect of treatments on carbon dioxide emission at fortnightly intervals, mg CO_2 100 g^{-1} soil (Continued...)

Treatments	7th fortnight	8th fortnight	9th fortnight	10th fortnight	11th fortnight	12th fortnight	Total emission
T_1	7.11	7.07	6.44	6.22	6.15	6.07	87.17
T_2	10.06	9.32	9.18	7.12	9.07	7.05	135.50
T_3	17.38	11.52	9.48	9.36	7.26	7.64	408.50
T_4	80.37	73.69	58.37	42.06	26.47	13.42	1014.05
T_5	6.78	6.53	6.31	6.03	5.21	4.05	143.10
T_6	7.86	7.50	7.18	6.63	5.70	5.10	200.69
T_7	4.75	4.38	4.33	4.32	3.63	3.54	56.60
CD (0.05)	0.764	0.403	0.264	0.412	0.289	0.375	16.292

Treatments

T_1 Biochar @ 1 per cent

T_2 Biochar @ 2 per cent

T_3 Farmyard Manure @ 1 per cent

T_4 Farmyard Manure @ 2 per cent

T_5 Vermicompost @ 1 per cent

T_6 Vermicompost @ 2 per cent

T_7 Control (no amendments)

In the first fortnight, the highest value for CO_2 emission (140.76 mg CO_2 100 g^{-1}) was recorded by T_4 which received FYM @ 2 per cent, followed by T_3 which received FYM @ 1 per cent (92.85 mg CO_2 100 g^{-1}), T_6 which received vermicompost @ 2 per cent (44.67 mg CO_2 100 g^{-1}), T_5 which received vermicompost @ 1 per cent (27.32 mg CO_2 100 g^{-1}), T_2 which received biochar @ 2 per cent (15.36 mg CO_2 100 g^{-1}) and T_1 which received biochar @ 1 per cent (8.67 mg CO_2 100 g^{-1}). The lowest emission was observed for the control treatment (without any amendment) which recorded 5.63 mg CO_2 100 g^{-1}.

In the second fortnight, the emission was decreased slightly from the first fortnight's emission in all the treatments. The treatment T_4 which received FYM @ 2 per cent recorded the highest value of 135.64 mg CO_2 100 g^{-1}, followed by T_3 which received FYM @ 1 per cent (76.45 mg CO_2 100 g^{-1}) and the lowest value was recorded by the control treatment (5.49 mg CO_2 100 g^{-1}).

In the third fortnight, the amount of CO_2 emitted was found to be decreased in all the treatments and the highest CO_2 emission of 127.26 mg CO_2 100 g^{-1} was recorded for the treatment that received FYM @ 2 per cent, followed by T_3 which received FYM @ 1 per cent (63.37 mg CO_2 100 g^{-1}) and the lowest value was recorded by the control (8.15 mg CO_2 100 g^{-1}).

During the incubation period, emission was decreased and it was observed that the treatment T_4 which received FYM @ 2 per cent recorded the highest values of 117.83 mg CO_2 100 g^{-1}, 105.38 mg CO_2 100 g^{-1}, 92.8 mg CO_2 100 g^{-1}, 80.37 mg CO_2 100 g^{-1}, 73.69 mg CO_2 100 g^{-1}, 58.37 mg CO_2 100 g^{-1}, 42.06 mg CO_2 100 g^{-1}, 26.47 mg CO_2 100 g^{-1} and 13.42 mg CO_2 100 g^{-1} respectively and the control treatment recorded the lowest values of 5.18, 5.03, 4.96, 4.75, 4.38, 4.33, 4.32 3.63 and 3.54 mg CO_2 100 g^{-1} respectively.

During the course of time, the emission was found to be decreased for all the treatments and in the case of FYM; emission was reduced to half of the initial CO_2 emission at 8th fortnight (73.69 mg CO_2 100 g^{-1}). At this time, biochar @ 2 per cent recorded a value of 9.32 mg CO_2 100 g^{-1}. The lowest value was recorded by the control (4.38 mg CO_2 100 g^{-1}). Considering soils incubated with biochar, we can observe a more or less constant emission during the experimental period.

Regarding total emission at the end of twelfth fortnight, the lowest emission of 56.60 mg CO_2 100 g^{-1} was recorded by the control treatment and the treatment that received biochar 1 per cent and 2 per cent registered an emission of 87.17 mg CO_2 100 g^{-1} and 135.50 mg CO_2 100 g^{-1}respectively. 143.10 mg CO_2 100 g^{-1} and 200.69 mg CO_2 100 g^{-1} were emitted when the soil was incubated with vermicompost @ 1 per cent and @ 2 per cent respectively. The highest emission was registered by the treatment which received FYM @ 2 per cent (1014.0532 mg CO_2 100 g^{-1}), followed by T_3 which received FYM @ 1 per cent (408.50 mg CO_2 100 g^{-1}). Hence, the order of emission is as follows: control < biochar @ 1 per cent < biochar 2 @ per cent < vermicompost @ 1 per cent < vermicompost @ 2 per cent < FYM @ 1 per cent < FYM @ 2 per cent. There was significant difference between the treatments in the emission of CO_2.

4. 3. FIELD EXPERIMENT

A general view of the experimental field has been presented in Plate 4.

4. 3. 1. Soil Analysis

4. 3. 1. 1. Effect of Treatments on Physical Properties of Soil

The physical properties of the soil at 50 per cent flowering stage and at harvest stage are presented in Table 32. It could be observed that all the physical properties were significantly influenced by the application of treatments.

4. 3. 1. 1. 1. Water Holding Capacity (WHC)

It can be observed from the data that WHC was significantly influenced by the treatments at 50 per cent flowering stage and at final harvest stage (Table 32). At fifty per cent flowering stage, treatment T_4 (biochar @ 30 t ha^{-1} + NPK as per POP) recorded significantly superior value of 48.78 per cent, followed by T_8 (40.67 per cent) which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as

Plate 4. General view of the experimental field

Table 32. Effect of treatments on physical properties of soil at fifty per cent flowering and final harvest stages

Treatments	Fifty per cent flowering				Final harvest			
	WHC (per cent)	Porosity (per cent)	Bulk density ($Mg\ m^{-3}$)	WSA (per cent)	WHC (per cent)	Porosity (per cent)	Bulk density ($Mg\ m^{-3}$)	WSA (per cent)
T_1	30.89	45.00	1.32	56.78	28.66	45.53	1.34	55.13
T_2	31.65	45.83	1.30	60.83	29.96	46.77	1.32	58.54
T_3	38.78	50.39	1.27	66.81	36.57	50.39	1.29	64.89
T_4	48.78	54.55	1.20	80.26	45.64	54.10	1.23	78.30
T_5	36.89	50.00	1.26	64.23	34.37	50.00	1.28	62.96
T_6	33.08	46.67	1.28	61.97	31.00	47.58	1.30	60.12
T_7	35.38	49.60	1.27	63.41	33.49	49.61	1.29	61.43
T_8	40.67	53.85	1.20	79.86	41.89	53.03	1.24	77.75
T_9	39.67	53.13	1.20	74.65	38.26	53.31	1.24	70.13
CD (0.05)	0.215	2.571	0.036	0.569	0.595	0.848	0.023	0.799

Treatments

T_1	Package of Practices Recommendation (KAU)
T_2	Biochar @ 10 t ha^{-1} + NPK as per POP
T_3	Biochar @ 20 t ha^{-1} + NPK as per POP
T_4	Biochar @ 30 t ha^{-1} + NPK as per POP
T_5	Biochar @ 20 t ha^{-1} + 75 per cent NPK as per POP
T_6	Biochar @ 10 t ha^{-1} + FYM @ 10 t ha^{-1} + 75 per cent NPK as per POP
T_7	Biochar @ 10 t ha^{-1} + vermicompost @ 5 t ha^{-1} + 75 per cent NPK as per POP
T_8	Biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP
T_9	Biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP

per POP and T_9 (biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP) which recorded a water holding capacity of 39.67 per cent. T_1 recorded the lowest WHC of 30.89 per cent and there observed an increase of 57.92 per cent in WHC by the application of biochar @ 30 t ha^{-1}.

At final harvest, all the treatments showed the similar trends, even though there was a slight decrease in WHC. Treatment T_4 (biochar @ 30 t ha^{-1} + NPK as per POP) recorded significantly higher value of 45.64 per cent, followed by T_8 (41.89 per cent) which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP and T_9 (38.26 per cent) which received biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP. The lowest WHC of 28.66 per cent was recorded by the treatment that received POP and there was 59.25 per cent increase in WHC by the application of biochar @ 30 t ha^{-1}.

4. 3. 1. 1. 2. Porosity

It was clear from the analytical data that biochar application had significant influence on soil porosity at 50 per cent flowering stage and at final harvest stage (Table 32).

At 50 per cent flowering stage, treatments T_4 (biochar @ 30 t ha^{-1} + NPK as per POP), T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP and T_9 (38.26 per cent) which received biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP recorded significantly superior values of 54.55, 53.85 and 53.13 per cent respectively and these treatments were found to be on par. The lowest porosity of 45.00 per cent was shown by T_1 which received POP. A similar trend was observed at final harvest stage also. T_4 (biochar @ 30 t ha^{-1} + NPK as per POP), T_8 (biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP) and T_9 which received biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP were found to be on par and showed porosity values of 54.10, 53.03 and 53.31 per cent respectively. The lowest value of 45.53 per cent was recorded by POP. There observed an increase in porosity by 21.22 and 18.82 per cent respectively at fifty per cent flowering stage and at final harvest stage by the application of biochar @ 30 t ha^{-1}.

4. 3. 1. 1.3. Bulk Density

Bulk density was found to be significantly influenced by the treatments at fifty per cent flowering and at final harvest stage (Table 32). At 50 per cent flowering stage, the lowest bulk density value of 1.20 Mg m^{-3} was recorded by T_4 (biochar @ 30 tha^{-1} + NPK as per POP), T_8 (biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP) and T_9 which received biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP. The highest bulk density was shown by T_1 which received POP (1.32) followed by T_2 (1.30) which received biochar @ 10 t ha^{-1} + NPK as per POP. At final harvest stage, all the treatments showed a decrease in bulk density and T_4 (biochar @ 30 t ha^{-1} + NPK as per POP) recorded the lowest value of 1.23, which was on par with T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP (1.24) and T_9 (biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP) which recorded a bulk density of 1.24. The highest value of 1.34 was shown by T_1 which received POP, followed by T_2 (1.32) which received biochar @ 10 t ha^{-1} + NPK as per POP. Bulk density was found to be increased by 9.09 and 8.20 per cent respectively at fifty per cent flowering stage and at final harvest stage.

4. 3. 1. 1.4. Water Stable Aggregates (WSA)

Per cent of WSA is taken as an index of aggregate stability. Statistical analysis of the data indicated that per cent of water stable aggregates were significantly influenced by the application of treatments (Table 32). At 50 per cent flowering stage, the per cent of WSA was significantly superior for the treatment T_4 (biochar @ 30 t ha^{-1} + NPK as per POP) which recorded a value of 80.26 per cent, which was on par with T_8 (79.86 per cent) which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP. The lowest per cent of water stable aggregates was shown by POP (56.78 per cent).

At final harvest stage, there showed a slight decrease in the per cent of WSA and T_4 (biochar @ 30 t ha^{-1} + NPK as per POP) showed the significantly superior value of 78.30 per cent, which was on par with T_8 (77.75 per cent) which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP. POP recorded the least value of 55.13 per cent.

4. 3. 1. 2. Effect of Treatments on Electro-Chemical and Chemical Properties of Soil

The data on electro-chemical and chemical properties of the soil by the application of treatments are presented in Table 33.

4. 3. 1. 2. 1. pH

Statistical analysis of the data indicated that there was significant difference between the treatments at fifty per cent flowering and at final harvest stage with respect to soil pH (Table 33). By the application of treatments, at 50 per cent flowering stage, there was an increase in pH, and towards harvest stage, all the values showed a decreasing trend. The initial soil pH was 4.80. At 50 per cent flowering stage, T_4 (biochar @ 30 t ha^{-1} + NPK as per POP) recorded the significantly superior value of 6.57, which was on par with T_8 (6.36) that received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP. At final harvest stage also, T_4 (biochar @ 30 t ha^{-1} + NPK as per POP) showed the significantly superior value of 5.99, followed by T_8 (biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP) that had pH of 5.60 and these two treatments were found to be on par.

4. 3. 1. 2. 2. Electrical Conductivity (EC)

It had been statistically observed that there was significant difference between the treatments at fifty per cent flowering and at final harvest stage with respect to EC (Table 33). By the application of treatments, at 50 per cent flowering stage, there was an increase in EC, and towards harvest stage, all the values showed a decreasing trend. The initial soil had an EC of was 0.42 dS m^{-1}. At 50 per

Table 33. Effect of treatments on electro-chemical and chemical properties of soil at fifty per cent flowering and final harvest stages

Treatments	Fifty per cent flowering			Final harvest		
	pH	EC (dS m^{-1})	CEC (cmol kg^{-1})	pH	EC (dS m^{-1})	CEC (cmol kg^{-1})
T_1	4.93	0.44	3.14	4.74	0.42	3.09
T_2	5.26	0.52	3.38	4.83	0.47	3.29
T_3	6.25	0.72	4.18	5.43	0.69	4.02
T_4	6.57	0.87	5.43	5.99	0.76	5.18
T_5	6.19	0.65	3.82	5.35	0.62	3.64
T_6	5.83	0.60	3.65	5.22	0.58	3.57
T_7	5.70	0.56	3.50	5.16	0.53	3.46
T_8	6.36	0.80	5.13	5.60	0.69	5.09
T_9	6.23	0.76	4.26	5.42	0.66	4.11
CD (0.05)	0.309	0.012	0.608	0.339	0.004	0.147

Treatments

T_1 Package of Practices Recommendation (KAU)

T_2 Biochar @ 10 t ha^{-1} + NPK as per POP

T_3 Biochar @ 20 t ha^{-1} + NPK as per POP

T_4 Biochar @ 30 t ha^{-1} + NPK as per POP

T_5 Biochar @ 20 t ha^{-1} + 75 per cent NPK as per POP

T_6 Biochar @ 10 t ha^{-1} + FYM @ 10 t ha^{-1} + 75 per cent NPK as per POP

T_7 Biochar @ 10 t ha^{-1} + vermicompost @ 5 t ha^{-1} + 75 per cent NPK as per POP

T_8 Biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP

T_9 Biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP

cent flowering stage, T_4 (biochar @ 30 t ha^{-1} + NPK as per POP) recorded the significantly superior value of 0.87 dS m^{-1}, followed by 0.80 dS m^{-1} which was recorded by the treatment T_8 that received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP and the least value of 0.44 dS m^{-1} was registered for the treatment that received POP. At final harvest stage also, T_4 (biochar @ 30 t ha^{-1} + NPK as per POP) showed the significantly superior value of 0.76 dS m^{-1}, followed by T_8 (0.69 dS m^{-1}) and the control treatment recorded the lowest value of 0.42 dS m^{-1}.

4. 3. 1. 2. 3. Cation Exchange Capacity (CEC)

Perusal of the data revealed that there was significant difference between the treatments at fifty per cent flowering and at final harvest stage with respect to soil CEC (Table 33). By the application of treatments, at 50 per cent flowering stage, there was an increase in CEC, and towards harvest stage, all the values showed a decreasing trend. The initial soil had CEC of 2.56 cmol (+) kg^{-1}. At 50 per cent flowering stage, T_4 (biochar @ 30 t ha^{-1} + NPK as per POP) recorded the significantly superior value of 5.43 cmol (+) kg^{-1}, which was on par with T_8 (5.13 cmol (+) kg^{-1}) that received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP. At final harvest stage also, T_4 (biochar @ 30 t ha^{-1} + NPK as per POP) showed the significantly superior value of 5.18 cmol (+) kg^{-1}, which was on par with T_8 (biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP) that had CEC of 5.09 cmol (+) kg^{-1}. The control treatment registered the value of 3.09 cmol (+) kg^{-1}.

4. 3. 1. 2. 4. Organic Carbon

The initial organic carbon content of the soil was 0.76 per cent and there observed an increase in the value by the application of treatments. It had been statistically verified that at fifty per cent flowering, there was significant difference between the treatments (Table 34). Significantly superior value of 1.43 per cent was shown by T_4, which was on par with T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP (1.32 per cent) and T_9 (1.27 per cent) which

Table 34. Effect of treatments on organic C, available N, available P and available K status of soil at fifty per cent flowering and final harvest stages

Treatments	Fifty per cent flowering				Final harvest			
	Organic C (per cent)	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	Organic C (per cent)	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})
T_1	0.79	232.65	80.86	142.67	0.68	226.89	77.56	117.08
T_2	1.03	258.00	85.56	145.35	0.96	253.67	79.15	121.76
T_3	1.19	280.79	109.86	157.63	1.12	276.54	106.90	138.11
T_4	1.43	296.75	100.68	175.43	1.36	289.65	95.98	163.99
T_5	1.10	278.30	114.20	152.58	1.06	273.15	105.95	130.92
T_6	1.07	274.15	93.44	148.03	1.04	269.77	89.65	128.98
T_7	1.05	266.64	119.80	159.37	1.01	260.79	110.45	144.26
T_8	1.32	295.45	124.58	174.86	1.28	286.43	118.03	158.02
T_9	1.27	289.60	126.09	162.72	1.19	280.78	122.63	142.47
CD (0.05)	0.198	2.064	NS	1.166	0.138	2.650	1.468	15.382

Treatments

T_1 Package of Practices Recommendation (KAU)

T_2 Biochar @ 10 t ha^{-1} + NPK as per POP

T_3 Biochar @ 20 t ha^{-1} + NPK as per POP

T_4 Biochar @ 30 t ha^{-1} + NPK as per POP

T_5 Biochar @ 20 t ha^{-1} + 75 per cent NPK as per POP

T_6 Biochar @ 10 t ha^{-1} + FYM @ 10 t ha^{-1} + 75 per cent NPK as per POP

T_7 Biochar @ 10 t ha^{-1} + vermicompost @ 5 t ha^{-1} + 75 per cent NPK as per POP

T_8 Biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP

T_9 Biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP

received biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP. The lowest value of 0.79 per cent was shown by the control treatment.

It has been statistically proved that the treatments had significant influence on organic C content of soil at final harvest stage also. The highest value of 1.36 per cent was shown by T_4 (biochar @ 30 t ha^{-1} + NPK as per POP) and it was found to be on par with T_8 (1.28 per cent) which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP. The lowest organic C content of 0.68 per cent was shown by POP treatment.

4. 3. 1. 2. 5. Available Nitrogen

It is evident from the data that by the application of treatments, there was increase in the availability of N in soil at 50 per cent flowering stage, followed by a decrease due to uptake of N by the plant at final harvest stage. There was significant difference between the treatments in availability of N due to application of treatments (Table 34). The highest availability of N was recorded by T_4 that received biochar @ 30 t ha^{-1} + NPK as per POP (296.75 kg ha^{-1}), which was significantly higher from all other treatments followed by T_8 (295.45 kg ha^{-1}) which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP and these two treatments were found to be on par. The lowest value of 232.65 kg ha^{-1} was recorded by the treatment that received POP.

At final harvest also, the same trend was observed. The significantly highest value of 289.65 kg ha^{-1} was recorded by T_4 (biochar @ 30 t ha^{-1} + NPK as per POP) followed by T_8 (286.43 kg ha^{-1}) which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP and T_9 (280.78 kg ha^{-1}) which received biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP. The lowest value of 226.89 kg ha^{-1} was recorded by the treatment which received POP.

4. 3. 1. 2. 6. Available Phosphorus

By the application of treatments, at first, there was an increase in available P status when compared to initial value (75.15 kg ha^{-1}) but towards harvest stage, there occurred a decrease. Statistical analysis of the data at fifty per cent flowering revealed that there was no significant difference between the treatments regarding availability of P in soil (Table 34). However, T_9 recorded the highest value of 126.09 kg ha^{-1} followed by T_8 (124.58 kg ha^{-1}) which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP and the lowest value of 80.86 kg ha^{-1} was recorded by the POP treatment. At final harvest stage, there was significant difference between the treatments. T_9 which received biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP recorded the highest value of 122.63 kg ha^{-1} followed by T_8 (118.03 kg ha^{-1}) which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP and the lowest value of 77.56 kg ha^{-1} was recorded by POP.

4. 3. 1. 2. 7. Available Potassium

Statistical analysis of the data indicated that treatments had significant influence on available K in soil (Table 34) both at fifty per cent flowering and at final harvest stage of the crop. T_4 (biochar @ 30 t ha^{-1} + NPK as per POP) recorded the superior value of 175.43 kg ha^{-1} and it was found to be on par with T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP which recorded 174.86 kg ha^{-1} and the lowest value of 142.67 kg ha^{-1} was recorded by the treatment that received POP.

At final harvest stage also, there was significant difference between the treatments. There observed a decrease in the value of available K in soil than that observed at fifty per cent flowering stage. T_4 which received biochar @ 30 t ha^{-1} + NPK as per POP recorded the superior value of 163.99 kg ha^{-1} and it was on par with T_8 (158.02 kg ha^{-1}) which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP and T_9 (142.47 kg ha^{-1}) which received biochar @ 20 t ha^{-1} +

AMF @ 200 g m^{-2} + NPK as per POP and the lowest value of 117.08 kg ha^{-1} was recorded by the treatment that received POP.

4. 3. 1. 2. 8. Exchangeable Calcium

It had been statistically observed that application of treatments had significant influence on available Ca in soil at fifty per cent flowering stage and at final harvest stage (Table 35). At fifty per cent flowering stage, T_4 which received biochar @ 30 t ha^{-1} + NPK as per POP recorded the value of 3.00 cmol kg^{-1} and it was on par with T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP and T_9 (2.5 cmol kg^{-1}) to which biochar was applied @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP. The lowest value was observed for T_1 (1.00 cmol kg^{-1}) which received POP.

At final harvest stage also, the same trend observed and there was slight decrease in available Ca in soil at final harvest stage that at fifty per cent flowering stage. T_4 (biochar @ 30 t ha^{-1} + NPK as per POP) recorded the superior value of 2.50 cmol kg^{-1} and it was found to be on par with T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP and T_9 (2.00 cmol kg^{-1}) which received biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP. The lowest value was observed for T_1 (0.50 cmol kg^{-1}).

4. 3. 1. 2. 9. Exchangeable Magnesium

Perusal of the data indicated that treatments had significant influence on available Mg in soil (Table 35) both at fifty per cent flowering and at final harvest stage of the crop. At fifty per cent flowering stage, T_4 (biochar @ 30 t ha^{-1} + NPK as per POP) and T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP recorded the superior value of 1.25 cmol kg^{-1} and this data was found to be on par with T_9 (1.00 cmol kg^{-1}) which received biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP. The lowest value of 0.25 cmol kg^{-1} was recorded by the treatment that received POP.

Table 35. Effect of treatments on exchangeable Ca, Mg and available S in soil at fifty per cent flowering and final harvest stages

Treatments	Fifty per cent flowering			Final harvest		
	Exchangeable Ca (c mol kg^{-1})	Exchangeable Mg (c mol kg^{-1})	Available S (mg kg^{-1})	Exchangeable Ca (cmol kg^{-1})	Exchangeable Mg (cmol kg^{-1})	Available S (mg kg^{-1})
T_1	1.00	0.25	8.95	0.50	0.15	7.56
T_2	1.00	0.50	10.85	0.50	0.25	9.96
T_3	2.00	0.75	13.56	1.50	0.75	13.18
T_4	3.00	1.25	15.08	2.50	1.00	14.76
T_5	1.50	0.75	12.45	1.00	0.50	11.75
T_6	1.50	0.50	10.65	1.00	0.25	9.95
T_7	2.00	1.00	13.65	1.50	0.75	12.45
T_8	2.50	1.25	16.46	2.00	1.00	15.58
T_9	2.50	1.00	14.87	2.00	0.75	13.65
CD (0.05)	0.81	0.361	1.047	0.748	0.294	1.194

Treatments

T_1 Package of Practices Recommendation (KAU)

T_2 Biochar @ 10 t ha^{-1} + NPK as per POP

T_3 Biochar @ 20 t ha^{-1} + NPK as per POP

T_4 Biochar @ 30 t ha^{-1} + NPK as per POP

T_5 Biochar @ 20 t ha^{-1} + 75 per cent NPK as per POP

T_6 Biochar @ 10 t ha^{-1} + FYM @ 10 t ha^{-1} + 75 per cent NPK as per POP

T_7 Biochar @ 10 t ha^{-1} + vermicompost @ 5 t ha^{-1} + 75 per cent NPK as per POP

T_8 Biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP

T_9 Biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP

It is clear from the data that there was significant difference between the treatments at final harvest stage also. There observed a decrease in the value of available Mg in soil than that observed at fifty per cent flowering stage. T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP and T_4 recorded the superior value of 1.00 cmol kg^{-1} and the lowest value of 0.15 cmol kg^{-1} was recorded by the treatment that received POP.

4. 3. 1. 2. 10. Available Sulphur

The data analysis revealed that treatments had significant influence on available S status in soil both at fifty per cent flowering stage and at harvest stage (Table 35). At fifty per cent flowering stage, T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP recorded the superior value of 16.46 kg ha^{-1}, followed by T_4 (15.08 kg ha^{-1}) which received biochar @ 30 t ha^{-1} + NPK as per POP and the lowest value of 8.95 kg ha^{-1} was recorded by the treatment that received POP.

There observed a decrease in the value of available S in soil at final harvest stage than that observed at fifty per cent flowering stage and there was significant difference between the treatments. T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP recorded the superior value of 15.58 kg ha^{-1} which was found to be on par with T_4 (biochar @ 30 tha^{-1} + NPK as per POP) which recorded 14.76 kg ha^{-1} and the lowest value of 7.56 kg ha^{-1} was recorded by the treatment that received POP.

4. 3. 1. 2. 11. Available Iron

It had been statistically observed that the treatments had significant influence on available Fe in soil both at fifty per cent flowering stage and at final harvest stage (Table 36). At fifty per cent flowering stage, T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP recorded the superior value of 28.22 mg kg^{-1}, followed by T_4 (biochar @ 30 t ha^{-1} + NPK as per POP)

Table 36. Effect of treatments on available Fe, Mn, Zn and Cu status of soil at fifty per cent flowering and final harvest stages, mg kg^{-1}

Treatments	Fifty per cent flowering				Final harvest			
	Fe	Mn	Zn	Cu	Fe	Mn	Zn	Cu
T_1	18.67	9.67	2.43	4.27	18.32	7.74	1.13	4.04
T_2	19.56	11.68	2.79	5.14	19.06	9.97	1.20	5.24
T_3	21. 98	13.57	3.21	7.05	20.23	11.87	1.82	6.76
T_4	26.77	20.25	5.32	10.47	25.13	21.56	3.96	9.53
T_5	21. 26	12.17	2.92	6.98	20.00	10.47	1.32	6.65
T_6	20.78	12.02	2.83	5.80	19.45	10.46	1.24	5.85
T_7	23.45	14.26	3.44	7.18	22.08	12.48	2.60	6.79
T_8	28.22	25.65	5.57	10.86	27.15	21.66	4.68	9.65
T_9	24.89	16.67	3.73	8.25	22.04	14.78	2.81	9.50
CD (0.05)	0.250	0.076	0.338	0.418	0.095	0.179	0.309	0.157

Treatments

T_1 Package of Practices Recommendation (KAU)

T_2 Biochar @ 10 t ha^{-1} + NPK as per POP

T_3 Biochar @ 20 t ha^{-1} + NPK as per POP

T_4 Biochar @ 30 t ha^{-1} + NPK as per POP

T_5 Biochar @ 20 t ha^{-1} + 75 per cent NPK as per POP

T_6 Biochar @ 10 t ha^{-1} + FYM @ 10 t ha^{-1} + 75 per cent NPK as per POP

T_7 Biochar @ 10 t ha^{-1} + vermicompost @ 5 t ha^{-1} + 75 per cent NPK as per POP

T_8 Biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP

T_9 Biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP

(26.77 mg kg^{-1}) and the lowest value of 18.67 mg kg^{-1} was recorded by the treatment that received POP.

At final harvest stage also, there was significant difference between the treatments. There observed a decrease in the value of available Fe than that observed at fifty per cent flowering stage. T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP recorded the superior value of 27.15 mg kg^{-1}, followed by T_4 that received biochar @ 30 t ha^{-1} + NPK as per POP (25.13 mg kg^{-1}) and the lowest value of 18.32 mg kg^{-1} was recorded by the treatment that received POP.

4. 3. 1. 2. 12. Available Manganese

Statistical analysis of the data revealed that the treatments had significant influence on available Mn in soil both at fifty per cent flowering stage and at final harvest stage (Table 36). At fifty per cent flowering stage, T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP recorded the superior value of 25.65 mg kg^{-1}, followed by T_4 that received biochar @ 30 tha^{-1} + NPK as per POP (20.25 mg kg^{-1}) and the lowest value of 9.67 mg kg^{-1} was recorded by the treatment that received POP.

There observed a decrease in the value of available Mn in soil was slightly decreased at final harvest stage than that observed at fifty per cent flowering stage and the treatments had significant influence on available Mn status of soil. T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP recorded the superior value of 21.66 mg kg^{-1}, followed by T_4 (21.56 mg kg^{-1}) that received biochar @ 30 t ha^{-1} + NPK as per POP and the lowest value of 7.74 mg kg^{-1} was recorded by the treatment that received POP.

4. 3. 1. 2. 13. Available Zinc

Perusal of the data revealed that application of treatments had significant influence on available Zn in soil at fifty per cent flowering stage and at final harvest stage (Table 36). At fifty per cent flowering stage, T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP recorded superior value 5.57 mg kg^{-1}, followed by T_4 (5.32 mg kg^{-1}) which received biochar @ 30 t ha^{-1} + NPK as per POP and the two treatments were found to be on par. The lowest value was observed for T_1 (2.43 mg kg^{-1}) which received POP.

Regarding available Zn status at final harvest stage, there was slight decrease when compared to that observed at fifty per cent flowering stage. T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP recorded superior value of 4.68 mg kg^{-1}, followed by T_4 (3.96 mg kg^{-1}) that received biochar @ 30 t ha^{-1} + NPK as per POP. The lowest value was observed for the treatment that received POP (1.13 mg kg^{-1}).

4. 3. 1. 2. 14. Available Copper

It was clear from the data that treatments had significant influence on the content of available Cu in soil both at fifty per cent flowering stage and at harvest stage (Table 36). At fifty per cent flowering stage, T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP recorded the superior value of 10.86 mg kg^{-1} and it was found to be on par with T_4 (10.47 mg kg^{-1}) which received biochar @ 30 t ha^{-1} + NPK as per POP and the lowest value of 4.27 mg kg^{-1} was recorded by the treatment that received POP.

At final harvest stage also, there was significant difference between the treatments. There observed a decrease in the value of available Cu in soil than that observed at fifty per cent flowering stage. T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP recorded the superior value of 9.65 mg kg^{-1}, followed by T_4 (9.53 mg kg^{-1}) which received biochar @ 30 t ha^{-1} + NPK as per POP and T_9 (9.50 mg kg^{-1}) which received biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP. The lowest value of 4.04 mg kg^{-1} was recorded by the treatment that received POP.

4. 3. 1. 3. Carbon Dioxide Emission in Field

The data is presented in Table 37 and a view of the experiment is depicted in Plate 5. The amount of carbon dioxide emitted as a result of application of different treatments was measured at fortnightly intervals in field during the crop growing period. Perusal of the data revealed that carbon dioxide emission in the field was significantly influenced by the treatments.

In the first fortnight the lowest emission was registered by the treatment T_2 that received biochar @ 10 t ha^{-1} + NPK as per POP, followed by T_5 that received biochar @ 20 t ha^{-1} + 75per cent NPK as per POP, T_3 (biochar @ 20 t ha^{-1} + NPK as per POP), T_4 (biochar @ 30 t ha^{-1} + NPK as per POP), T_9 (biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP), T_8 (biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP), T_7 (biochar @ 10 t ha^{-1} + vermicompost @ 5 t ha^{-1} + 75 per cent NPK as per POP), T_6 (biochar @ 10 t ha^{-1} + FYM @ 10 t ha^{-1}+75 per cent NPK as per POP). The highest emission was reported by the tretament that received POP.

The same trend was observed at all the fortnights and there observed a decrease in the emission in all the treated plots as the time progressed.

Regarding total emission of carbon dioxide in field, the lowest emission of 34.87 μg CO_2 m^{-2} was observed for the treatment T_2 that received biochar @ 10 t ha^{-1} + NPK as per POP, followed by 58.89 μg CO_2 m^{-2} which was emitted by the treatment T_5 that received biochar @ 20 t ha^{-1} + 75 per cent NPK as per POP. Treatment T_3 (biochar @ 20 t ha^{-1} + NPK as per POP), T_4 (biochar @ 30 t ha^{-1} + NPK as per POP), T_9 (biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP), T_8 (biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP), T_7 (biochar @ 10 t ha^{-1} + vermicompost @ 5 t ha^{-1} + 75 per cent NPK as per POP), T_6 (biochar @ 10 t ha^{-1} + FYM @ 10 t ha^{-1}+75 per cent NPK as per POP) recorded the emission of 63.77 μg CO_2 m^{-2}, 74.89 μg CO_2 m^{-2}, 77.53 μg CO_2 m^{-2}, 92.04 μg CO_2 m^{-2}, 125.22 μg CO_2 m^{-2}, 315.72 μg CO_2 m^{-2} and 592.29 μg CO_2 m^{-2} respectively.

Plate 5. A view of carbon dioxide emission study in field

Table 37. Effect of treatments on carbon dioxide emission in field at fortnightly intervals, µg CO_2 m^{-2}

Treatments	1st fortnight	2nd fortnight	3rd fortnight	4th fortnight	5th fortnight	6th fortnight	Total emission
T_1	152.88	127.66	107.53	85.84	68.24	50.14	592.29
T_2	6.86	6.39	5.75	5.48	5.34	5.05	34.87
T_3	11.83	11.53	11.05	10.68	9.57	9.11	63.77
T_4	13.40	13.88	12.67	12.18	12.03	10.73	74.89
T_5	10.94	10.72	10.45	9.45	9.28	8.05	58.89
T_6	81.65	68.95	55.27	46.57	35.73	27.55	315.72
T_7	24.11	23.56	22.45	19.59	18.22	17.29	125.22
T_8	16.34	15.87	15.54	15.07	14.74	14.48	92.04
T_9	15.56	14.06	12.83	12.47	12.16	10.45	77.53
CD (0.05)	1.881	1.098	0.527	0.738	0.898	0.862	2.287

Treatments

T_1 Package of Practices Recommendation (KAU)

T_2 Biochar @ 10 t ha^{-1} + NPK as per POP

T_3 Biochar @ 20 t ha^{-1} + NPK as per POP

T_4 Biochar @ 30 t ha^{-1} + NPK as per POP

T_5 Biochar @ 20 t ha^{-1} + 75 per cent NPK as per POP

T_6 Biochar @ 10 t ha^{-1} + FYM @ 10 t ha^{-1} + 75 per cent NPK as per POP

T_7 Biochar @ 10 t ha^{-1} + vermicompost @ 5 t ha^{-1} + 75 per cent NPK as per POP

T_8 Biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP

T_9 Biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP

4. 3. 2. Effect of Different Treatments on Biometric Characters of Yard Long Bean

4. 3. 2.1. Days to First Flowering

Regarding this parameter, there was significant difference between the treatments (Table 38). Treatment which received T_8 took significantly shorter duration of 28 days, followed by T_4 (biochar @ 30 t ha^{-1} + NPK as per POP) and T_9 (biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP) which took 29 days for first flowering. Treatment that received POP (T_1) took comparatively longer days of 33 for first flowering and it was on par with T_2 (biochar @ 10 t ha^{-1} + NPK as per POP) which recorded 32 days for first flowering.

4. 3. 2. 2. *Days to Fifty Per Cent Flowering*

Perusal of the data revealed that there was significant difference between the treatments regarding this parameter (Table 38). Among the treatments, T_8 (biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP) took comparatively shorter duration of 33 days, followed by T_9 (biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP), T_5 (biochar @ 20 t ha^{-1} + 75 per cent NPK as per POP) and T_7 (biochar @ 10 t ha^{-1} + vermicompost @ 5 t ha^{-1} + 75 per cent NPK as per POP) which took 35 days for fifty per cent flowering. T_1 (POP) showed comparatively longer duration of 41 days, followed by T_2 (biochar @ 10 t ha^{-1} + NPK as per POP) which took 40 days.

4. 3. 2. 3. Duration from Flowering to Final Harvest

Statistical analysis of the data revealed that the treatments had significant influence on duration from flowering to final harvest stage of the crop (Table 38). The longer duration (from flowering to final harvest) of 81 days was observed for the treatment which received T_8 (biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP) and it was found to be on par with T_4 (biochar @ 30 t ha^{-1} + NPK as per POP) (79 days). It was followed by T_9 (biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} +

Table 38. Effect of treatments on biometric characters of yard long bean

Treatments	Days to first flowering	Days to fifty per cent flowering	Duration from flowering to final harvest (days)	Number of nodules plant^{-1}	Weight of nodules plant^{-1} (g)
T_1	33	41	60	4	0.23
T_2	32	40	66	6	0.35
T_3	30	35	73	10	0.76
T_4	29	34	79	17	1.50
T_5	30	36	72	8	0.53
T_6	32	36	71	8	0.43
T_7	30	35	76	11	0.98
T_8	28	33	81	18	1.95
T_9	29	35	76	12	1.34
CD (0.05)	2.496	0.903	3.119	1.988	0.098

Treatments

T_1	Package of Practices Recommendation (KAU)
T_2	Biochar @ 10 t ha^{-1} + NPK as per POP
T_3	Biochar @ 20 t ha^{-1} + NPK as per POP
T_4	Biochar @ 30 t ha^{-1} + NPK as per POP
T_5	Biochar @ 20 t ha^{-1} + 75 per cent NPK as per POP
T_6	Biochar @ 10 t ha^{-1} + FYM @ 10 t ha^{-1} + 75 per cent NPK as per POP
T_7	Biochar @ 10 t ha^{-1} + vermicompost @ 5 t ha^{-1} + 75 per cent NPK as per POP
T_8	Biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP
T_9	Biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP

NPK as per POP) and T_7 (biochar @ 10 t ha^{-1} + vermicompost @ 5 t ha^{-1} + 75 per cent NPK as per POP), where the duration was 76 days. The shorter duration of 60 days was observed for T_1 (POP).

4. 3. 2. 4. Number of Nodules Plant^{-1}

It had been statistically verified that the number of nodules per plant was significantly influenced by the treatments (Table 38). Treatment T_8 (biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP) recorded significantly superior value of 18 per plant and it was on par with T_4 (biochar @ 30 t ha^{-1} + NPK as per POP) which recorded 17 nodules per plant. The lowest number of root nodules per plant was observed for POP (4).

4. 3. 2. 5. Weight of Nodules Plant^{-1}

The data analysis showed that treatments had significant influence on weight of nodules per plant and T_8 (biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP) recorded significantly superior weight of 1.95 g per plant, followed by 1.50g for T_4 (biochar @ 30 t ha^{-1} + NPK as per POP). T_9 (biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP) recorded the value of 0.980 g and the least value of 0.230 g was recorded by treatment which received POP. (Table 38)

4. 3. 2. 6. Vine Length

The data analysis showed that application of treatments had significant influence on vine length at vegetative stage, flowering stage and harvesting stage (Table 39). At the vegetative stage, T_8 (biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP) recorded the significantly superior values of 192 cm and it was found to be on par with T_4 which received biochar @ 30 t ha^{-1} + NPK as per POP (190.50 cm) and T_9 that received biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP (190.00 cm). The least value of 173.50 cm was recorded by the control treatment (POP).

At flowering stage, there observed significant increase in vine length of yard long bean. Application of biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as

Table 39. Effect of treatments on vine length and number of leaves per plant at different growth stages

Treatments	Vine length (cm)			Number of leaves per plant		
	Vegetative stage	Flowering stage	Harvesting stage	Vegetative stage	Flowering stage	Harvesting stage
T_1	173.50	289.50	420.50	30	52	192
T_2	180.00	294.00	460.00	33	59	210
T_3	185.50	299.00	486.50	36	65	220
T_4	190.50	318.50	509.50	38	72	232
T_5	184.00	299.50	483.00	34	64	216
T_6	183.50	295.50	478.90	34	62	213
T_7	185.00	305.00	495.00	38	67	225
T_8	192.00	320.00	517.50	39	76	240
T_9	190.00	310.00	501.50	38	68	228
CD (0.05)	2.992	3.060	5.335	1.438	1.859	1.999

Treatments

T_1 Package of Practices Recommendation (KAU)

T_2 Biochar @ 10 t ha^{-1} + NPK as per POP

T_3 Biochar @ 20 t ha^{-1} + NPK as per POP

T_4 Biochar @ 30 t ha^{-1} + NPK as per POP

T_5 Biochar @ 20 t ha^{-1} + 75 per cent NPK as per POP

T_6 Biochar @ 10 t ha^{-1} + FYM @ 10 t ha^{-1} + 75 per cent NPK as per POP

T_7 Biochar @ 10 t ha^{-1} + vermicompost @ 5 t ha^{-1} + 75 per cent NPK as per POP

T_8 Biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP

T_9 Biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP

per POP (T_8) recorded the signifiacantly superior value of 320 cm and it was on par with treatment T_4 which received biochar @ 30 t ha^{-1} + NPK as per POP (318.50 cm). The control treatment (POP) registered the lowest value of 289.50 cm.

At harvesting stage also, the treatments had significant influence on vine length and treatment T8 was found to be the best with a vine length of 517.50 cm, followed by T_4 (biochar @ 30 t ha^{-1} + NPK as per POP) having a value of 509.50 cm. The least value of 420.50 cm was registered by the treatment that received POP.

4.3.2.7. Leaves per Plant

It is clear from the data that application of treatments had significant effect on number of leaves per plant at all the three stages of the crop (Table 39). At vegetative stage, treatment T_8 that received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP recorded the highest number of leaves (39). Treatments that received T_4 (biochar @ 30 t ha^{-1} + NPK as per POP), T_7 (biochar @ 10 t ha^{-1} + vermicompost @ 5 t ha^{-1} + 75 per cent NPK as per POP) and T_9 (biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP) recorded 38 leaves and it was found to be on par with T_8. Treatments that received POP recorded the lowest number of leaves (30).

As per the data from the field experiment, it is evident that the treatment T_8 that received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP registerd the significantly superior values of 76 and 240 number of leaves respectively at flowering stage and harvesting stage, followed by T_4 (biochar @ 30 t ha^{-1} + NPK as per POP) which had 72 and 232 number of leaves respectively. The lowest number of leaves was oberved for the treatment that received POP (52 and 192).

4. 3. 3. Effect of Treatments on Yield Attributes of Yard Long Bean

The data is presented in Table 40.

Table 40. Effect of treatments on yield attributes of yard long bean

Treatments	Pod length (cm)	Pod girth (cm)	Mean pod weight (g)	Pods plant^{-1}
T_1	45.30	2.10	22.56	39
T_2	48.20	2.60	25.45	44
T_3	50.50	3.20	25.68	47
T_4	52.80	3.70	25.76	49
T_5	49.80	2.90	25.83	46
T_6	48.60	2.90	25.38	45
T_7	51.70	3.00	25.87	47
T_8	54.50	3.90	26.63	51
T_9	52.60	3.40	25.73	48
CD (0.05)	0.769	0.231	0.982	1.332

Treatments

T_1 Package of Practices Recommendation (KAU)

T_2 Biochar @ 10 t ha^{-1} + NPK as per POP

T_3 Biochar @ 20 t ha^{-1} + NPK as per POP

T_4 Biochar @ 30 t ha^{-1} + NPK as per POP

T_5 Biochar @ 20 t ha^{-1} + 75 per cent NPK as per POP

T_6 Biochar @ 10 t ha^{-1} + FYM @ 10 t ha^{-1} + 75 per cent NPK as per POP

T_7 Biochar @ 10 t ha^{-1} + vermicompost @ 5 t ha^{-1} + 75 per cent NPK as per POP

T_8 Biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP

T_9 Biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP

4. 3. 3.1. Pod Length

Perusal of the data on pod length revealed that there was significant difference between the treatments regarding this parameter (Table 40). T_8 (biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP) recorded significantly superior value of 54.50 cm, followed by T_4 (52.80 cm) which received biochar @ 30 t ha^{-1} + NPK as per POP. The lowest value of 45.30 cm was recorded by the treatment which received POP. The pod length was found to be increased by 20.31 per cent by the application of biochar @ 20 t ha$^{-1.}$

4. 3. 3. 2. Pod Girth

The data analysis showed that pod girth was significantly influenced by the treatments (Table 40). T_8 (biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP) recorded the superior value of 3.90 cm and it was on par with T_4 (biochar @ 30 t ha^{-1} + NPK as per POP) that recorded a value of 3.50 cm. The least value of 2.10 cm was shown by POP. There observed an increase of 36.84 per cent in pod girth by the application of biochar @ 20 tha^{-1} + 2 per cent PGPR + NPK as per POP.

4. 3. 3.3. Pod Weight

Statistical analysis of the data indicated that mean pod weight was significantly influenced by the treatments (Table 40). T_8 (Biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP) recorded significantly superior value of 26.63 g. It was found to be on par with T_5 (25.87 g) that received biochar @ 20 t ha^{-1} + 75 per cent NPK as per POP, T_4 (25.83 g) which received biochar @ 30 t ha^{-1} + NPK as per POP, T_9 (biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP) which recorded a mean pod weight of 25.76 g, T_7 (25.73 g) which received biochar @ 10 t ha^{-1} + vermicompost @ 5 t ha^{-1} + 75 per cent NPK as per POP and T_3 (biochar @ 20 t ha^{-1} + NPK as per POP) which recorded a mean pod weight of 25.68 g. The treatment which received POP showed the least value of 22.56 g. There was an increase of 18.04 per cent in the mean weight of cowpea pods by the application of biochar @ 20 t ha^{-1}.

4. 3. 3.4. Pods Plant^{-1}

Considering number of pods per plant, significant difference was observed between the treatments (Table 40). T_8 (biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP) recorded significantly superior number of 51 pods per plant, followed by T_4 (49) which received biochar @ 30 t ha^{-1} + NPK as per POP and T_9 (48) which received biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP, Treatment that received POP recorded the lowest value of 39 pods per plant.

4. 3. 3.5. Yield Plant^{-1}

It had been statistically observed that the treatments had significant influence on yield of yard long bean (Table 41). T_8 (biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP) recorded significantly superior yield of 1358 g per plant, followed by T_4 (1262 g plant^{-1}) which received biochar @ 30 t ha^{-1} + NPK as per POP and T_9 (1235 g plant^{-1}) which received biochar @ 10 t ha^{-1} + vermicompost @ 5 t ha^{-1} + 75 per cent NPK as per POP. Treatment that received POP recorded the lowest yield of 880 g plant^{-1}. The yield was found to be increased by 54.32 per cent by the application of biochar @ 20 t ha^{-1}. Application of biochar @ 10 t ha^{-1} along with NPK resulted in the yield of 1120.00 g plant^{-1}, whereas biochar @ 20 t ha^{-1} along with NPK registered the yield of 1207 g plant^{-1} and biochar application @ 30 t ha^{-1} along with NPK recorded the yield of 1262.00 g plant^{-1}.

Treatment T_8 (biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP) registered the significantly superior yield of 20.12 t ha^{-1}, followed by T_4 (biochar @ 30 t ha^{-1} + NPK as per POP) with the yield of 18.70 t ha^{-1} and T_9 (18.30 t ha^{-1}) which received biochar @ 10 t ha^{-1} + vermicompost @ 5 t ha^{-1} + 75 per cent NPK as per POP. The lowest yield of 13.04 t ha^{-1} was registered by the treatment that received POP. When 10 t ha^{-1} biochar was applied along with NPK, the yield obtained was 16.59 t ha^{-1}, whereas biochar @ 20 t ha^{-1} along with NPK registered the yield of 17.88 t ha^{-1} and biochar application @ 30 t ha^{-1} along with NPK

Table 41. Effect of treatments on pod yield, Total Dry Matter production, Harvest Index, B: C ratio and pod protein of yard long bean

Treatments	Pod yield		Bhusa yield (g plant^{-1})	Total Dry Matter production (kg ha^{-1})	Harvest Index	B: C ratio	Pod protein (per cent)
	g plant^{-1}	t ha^{-1}					
T_1	880	13.04	507	2465.81	0.63	1.20	14.38
T_2	1120	16.59	532	2936.93	0.68	1.31	16.00
T_3	1207	17.88	549	3121.82	0.69	1.36	17.13
T_4	1262	18.70	582	3278.26	0.68	1.46	20.00
T_5	1188	17.60	544	3079.15	0.69	1.35	16.69
T_6	1142	16.92	538	2986.70	0.68	1.43	16.25
T_7	1216	18.02	553	3144.93	0.69	1.42	18.75
T_8	1358	20.12	610	3498.71	0.69	1.56	21.44
T_9	1235	18.30	564	3198.26	0.69	1.24	19.75
CD (0.05)	17.503	0.260	3.41	129.303	0.032	0.085	0.326

Treatments

T_1	Package of Practices Recommendation (KAU)
T_2	Biochar @ 10 t ha^{-1} + NPK as per POP
T_3	Biochar @ 20 t ha^{-1} + NPK as per POP
T_4	Biochar @ 30 t ha^{-1} + NPK as per POP
T_5	Biochar @ 20 t ha^{-1} + 75 per cent NPK as per POP
T_6	Biochar @ 10 t ha^{-1} + FYM @ 10 t ha^{-1} + 75 per cent NPK as per POP
T_7	Biochar @ 10 t ha^{-1} + vermicompost @ 5 t ha^{-1} + 75 per cent NPK as per POP
T_8	Biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP
T_9	Biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP

recorded the yield of 18.70 t ha^{-1}. A view of the pods obtained from the best, better and the control treatments are depicted in Plate 6.

*4. 3. 3.6. **Bhusa Yield Plant^{-1}***

The data analysis showed that bhusa yield per plant was significantly influenced by the treatments (Table 41). T_8 (biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP) recorded the superior value of 610.00 g $plant^{-1}$, followed by T_4 (biochar @ 30 t ha^{-1} + NPK as per POP) that recorded a value of 582.00 g $plant^{-1}$. The least value of 507.00 g $plant^{-1}$ was shown by POP.

*4. 3. 3. 7. **Total Dry Matter Production (kg ha^{-1})***

The data analysis showed that Total Dry Matter production (pod yield + bhusa yield) of the crop had significantly influenced by the treatments (Table 41). T_8 (biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP) recorded significantly superior dry matter production of 3498.71 kg ha^{-1}, followed by T_4 (3278. 26 kg ha^{-1}) which received biochar @ 30 t ha^{-1} + NPK as per POP and the treatment which received POP recorded the least value of 2465.81 kg ha^{-1}. There observed an increase by 41.88 per cent by the application of biochar @ 20 t ha^{-1}.

*4. 3. 3.8. **Harvest Index***

Statistical analysis of the data indicated that harvest index was significantly influenced by the treatments (Table 41). T_3 (biochar @ 20 t ha^{-1} + NPK as per POP), T_5 (biochar @ 20 t ha^{-1} + 75 per cent NPK as per POP), T_7 (biochar @ 10 t ha^{-1} + vermicompost @ 5 t ha^{-1} + 75 per cent NPK as per POP), T_8 (biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP), T_9 (Biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP) recorded significantly superior values of 0.69, followed by T_2 (biochar @ 10 t ha^{-1} + NPK as per POP), T_6 (biochar @ 10 t ha^{-1} + FYM @ 10 t ha^{-1}+75 per cent NPK as per POP) and T_4 (biochar @ 30 t ha^{-1} + NPK as per POP) which had harvest index of 0.68 and all the treatments were found to be on par except T_1 that received POP (0.63).

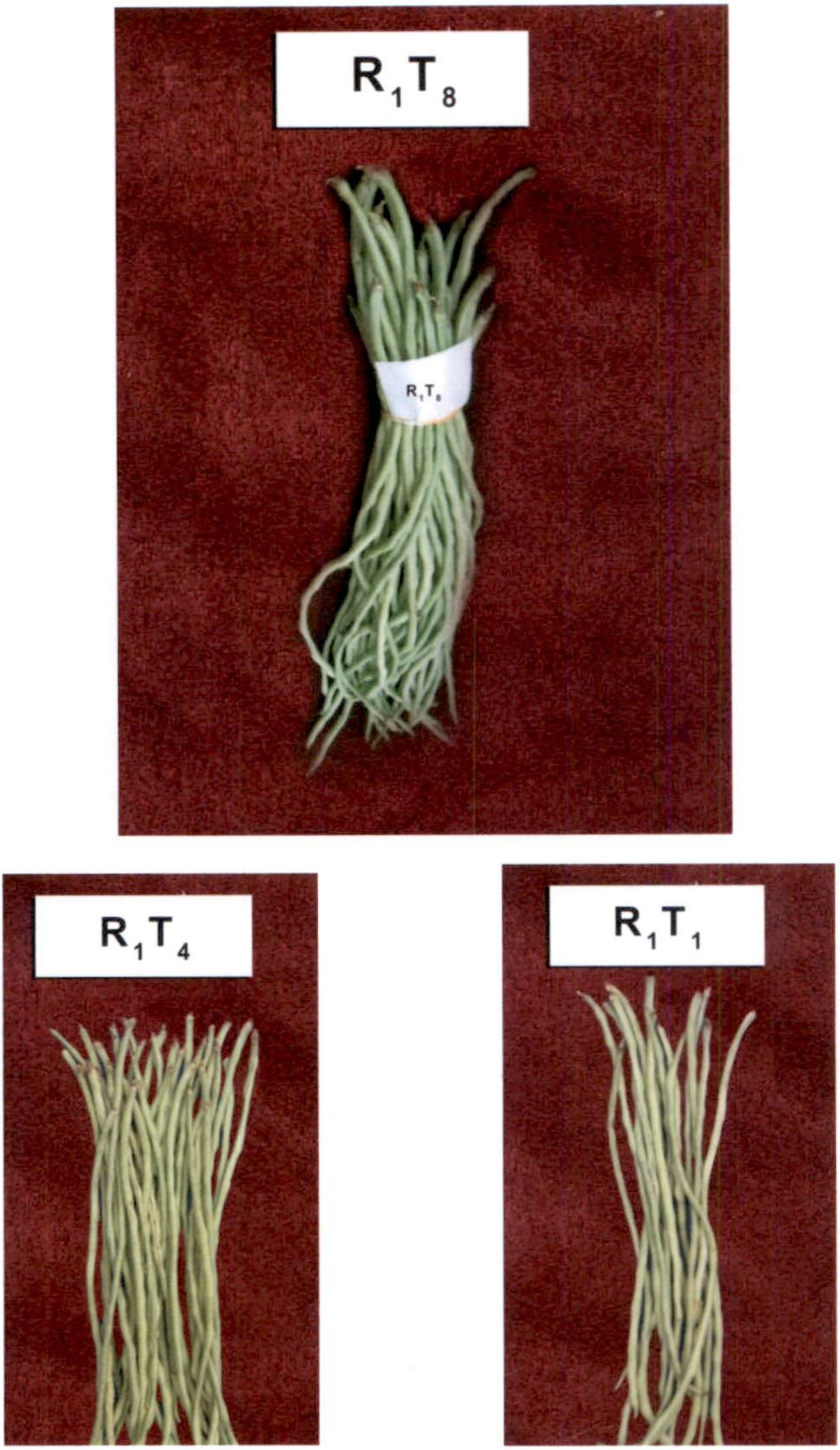


Plate 6. A view of the best, better and control treatments with respect to yield

4. 3. 3.9. B: C Ratio

From the experimental data, it can be observed that the treatments had significant influence on B: C ratio (Table 41). Significantly superior ratio of 1.56 was registered for the treatment T_8 (biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP), followed by T_4 (biochar @ 30 t ha^{-1} + NPK as per POP) where the B: C ratio was 1.46. The lowest B: C ratio was recorded by the treatment that received POP (1.20).

4. 3. 3.10. Pod Protein

It is clear from the data that treatments had significant influence on pod protein content of yard long bean (Table 41). T_8 (biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP recorded significantly superior protein content of 21.44 per cent, followed by T_4 (biochar @ 30 tha^{-1} + NPK as per POP)) which recorded a protein content of 20.00 per cent and then by T_9 which received biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP (19.75 per cent). The lowest protein content of 6.81 per cent was recorded by the control treatment. There observed an increase of 14.38 per cent in the pod protein content by the application of biochar @ 30 t ha^{-1}.

4. 3.4. Plant Analysis

Shoot and pod portion were analysed for major and micronutrients (N, P, K, Ca, Mg, S, Fe, Mn, Zn and Cu) at fifty per cent flowering stage and at final harvest stage (Table 42).

4.3.4.1. Shoot Analysis

4.3.4.1. 1. Nitrogen

Statistical analysis of the data revealed that application of treatments had significant influence on N content in shoot both at fifty per cent flowering stage and at final harvest stage (Table 42). At fifty per cent flowering stage, T_8 which received biochar @ 20 tha^{-1} + 2 per cent PGPR + NPK as per POP recorded the

Table 42. Effect of treatments on N, P and K content in shoot at fifty per cent flowering and final harvest stages, per cent.

Treatments	Fifty per cent flowering			Final harvest		
	N	P	K	N	P	K
T_1	2.29	0.206	1.30	2.00	0.200	1.11
T_2	2.42	0.232	1.54	2.18	0.240	1.16
T_3	2.65	0.258	2.00	2.51	0.260	1.98
T_4	3.18	0.270	2.36	2.74	0.280	2.13
T_5	2.54	0.250	1.97	2.40	0.250	1.92
T_6	2.52	0.248	1.58	2.29	0.250	1.60
T_7	3.00	0.262	2.06	2.60	0.270	2.03
T_8	3.30	0.285	2.30	3.05	0.300	2.10
T_9	3.06	0.320	2.28	2.65	0.320	2.05
CD (0.05)	0.049	0.005	0.131	0.060	0.006	0.038

Treatments

T_1 Package of Practices Recommendation (KAU)

T_2 Biochar @ 10 t ha^{-1} + NPK as per POP

T_3 Biochar @ 20 t ha^{-1} + NPK as per POP

T_4 Biochar @ 30 t ha^{-1} + NPK as per POP

T_5 Biochar @ 20 t ha^{-1} + 75 per cent NPK as per POP

T_6 Biochar @ 10 t ha^{-1} + FYM @ 10 t ha^{-1} + 75 per cent NPK as per POP

T_7 Biochar @ 10 t ha^{-1} + vermicompost @ 5 t ha^{-1} + 75 per cent NPK as per POP

T_8 Biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP

T_9 Biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP

significantly superior value of 3.30 per cent, followed by T_4 to which biochar was applied @ 30 t ha^{-1} + NPK as per POP (3.18 per cent). The lowest value was observed for POP (2.29 per cent).

At final harvest stage also, the same trend was observed and there observed slight decrease in N content in shoot at final harvest stage than that at fifty per cent flowering stage. T_8 which received biochar @ 20 t ha^{-1} along with 2 per cent PGPR and NPK as per POP recorded superior value of 3.05 per cent, followed by T_4 (2.74 per cent) to which biochar was applied @ 30 t ha^{-1} + NPK as per POP. Treatment that received POP registered the lowest value of 2.00 per cent.

4. 3. 4. 1. 2. Phosphorus

Statistical analysis of the data revealed that there was significant difference between the treatments at fifty per cent flowering and at final harvest stage of the crop (Table 42). T_9 which received biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP recorded the significantly superior value of 0.320 per cent followed by T_8 (0.285 per cent) which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP and the control treatment that received POP recorded the lowest value of 0.206 per cent.

Considering P content in shoot at final harvest stage, application of biochar had significant influence on this parameter and there observed a decrease in the value of P content in shoot than that observed at fifty per cent flowering stage. T_9 which received biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP as per POP recorded the superior value of 0.320 per cent followed by T_8 (0.30 per cent) where biochar was applied @ 20 t ha^{-1} along with 2 per cent PGPR and NPK as per POP and the lowest value of 0.200 per cent was recorded by POP.

4. 3. 4. 1. 3. Potassium

It is evident from the data indicated that treatments had significant influence on K content in shoot (Table 42) both at fifty per cent flowering and at final harvest stage of the crop. T_4 (biochar @ 30 t ha^{-1} along with NPK as per POP) recorded the superior value of 2.36 per cent and it was found to be on par with T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP (2.30 per cent) to which biochar was applied @ 30 t ha^{-1} along with NPK as per POP and T_9 (2.28 per cent) which received biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP and treatment that received POP registered the lowest value of 1.30 per cent.

At final harvest stage, there observed was significant difference between the treatments. K content in shoot was slightly lesser compared to the value registered at fifty per cent flowering stage. T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP recorded the superior value of 2.13 per cent, and it was on par with T_4 (2.10 per cent) which received biochar @ 30 t ha^{-1} + NPK as per POP, followed by T_4 (2.10 per cent) which received biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP and the lowest value of 1.11 per cent was recorded by the treatment that received POP..

4. 3.4.1. 4. Calcium

The data analysis showed that application of treatments had significant influence on Ca content in shoot both at fifty per cent flowering stage and at final harvest stage (Table 43). At fifty per cent flowering stage, treatment T_8 to which biochar was applied @ 20 t ha^{-1} along with 2 per cent PGPR + NPK as per POP recorded the significantly superior value of 2.87 per cent and it was on par with T_4 (2.84 per cent) which received biochar @ 30 t ha^{-1} + NPK as per POP. The control treatment that received POP recorded the lowest value of 1.28 per cent.

At final harvest stage also, the same trend was observed and there was slight decrease in Ca content at final harvest stage than at fifty per cent flowering

Table 43. Effect of treatments on Ca, Mg and S content in shoot at fifty per cent flowering and final harvest stages, per cent.

Treatments	Fifty per cent flowering			Final harvest		
	Ca	Mg	S	Ca	Mg	S
T_1	1.28	0.231	0.190	1.16	0.212	0.175
T_2	1.30	0.284	0.279	1.19	0.278	0.267
T_3	2.48	0.331	0.307	2.17	0.290	0.300
T_4	2.84	0.358	0.346	2.32	0.314	0.330
T_5	2.46	0.295	0.298	1.64	0.286	0.273
T_6	1.73	0.289	0.287	1.43	0.282	0.264
T_7	2.48	0.336	0.317	2.20	0.296	0.309
T_8	2.87	0.387	0.365	2.40	0.349	0.338
T_9	2.80	0.342	0.328	2.24	0.303	0.312
CD (0.05)	0.039	0.003	0.004	0.054	0.004	0.025

Treatments

T_1 Package of Practices Recommendation (KAU)

T_2 Biochar @ 10 t ha^{-1} + NPK as per POP

T_3 Biochar @ 20 t ha^{-1} + NPK as per POP

T_4 Biochar @ 30 t ha^{-1} + NPK as per POP

T_5 Biochar @ 20 t ha^{-1} + 75 per cent NPK as per POP

T_6 Biochar @ 10 t ha^{-1} + FYM @ 10 t ha^{-1} + 75 per cent NPK as per POP

T_7 Biochar @ 10 t ha^{-1} + vermicompost @ 5 t ha^{-1} + 75 per cent NPK as per POP

T_8 Biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP

T_9 Biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP

stage. T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP recorded superior value of 2.40 per cent, followed by T_4 (2.32 per cent) which received biochar @ 30 t ha^{-1} + NPK as per POP. The lowest value was observed for T_1 (1.16 per cent).

4. 3. 4. 1. 5. Magnesium

Statistical analysis of the data indicated that content of Mg in shoot was significantly influenced by the treatments (Table 43) both at fifty per cent flowering stage and at final harvest stage of the crop. At fifty per cent flowering stage, T_8 recorded the superior value of 0.387 per cent, followed by T_4 (0.358 per cent) which received biochar @ 30 t ha^{-1} + NPK as per POP and the lowest value of 0.231 per cent was recorded by the treatment that received POP at fifty per cent flowering stage.

It is clear from the data that Mg content was observed to be decreased at final harvest stage than that at fifty per cent flowering stage. Significantly superior value of 0.349 per cent was registered by T_8, followed by T_4 (0.314 per cent) which received biochar @ 30 t ha^{-1} + NPK as per POP and the lowest value of 0.212 per cent was recorded by the treatment to which POP was applied.

4. 3. 4. 1. 6. Sulphur

Perusal of the data revealed that treatments had significant influence on the content of S in shoot both at fifty per cent flowering stage and at harvest stage (Table 43). At fifty per cent flowering stage, T_8 recorded the superior value of 0.365 per cent, followed by T_4 (0.346 per cent) to which biochar was applied @ 30 t ha^{-1} along with NPK as per POP and the lowest value was registered by POP (0.190 per cent).

At final harvest stage also, there was significant difference between the treatments. There observed a decrease in the value of S content than that observed at fifty per cent flowering stage. T_8 recorded the superior value of 0.338 per cent which was found to be on par with T_4 (0.330 per cent) which received biochar @ 30 t ha^{-1} + NPK as per POP and the lowest value of 0.175 per cent was recorded by the treatment that received POP.

4.3.4.1. 7. Iron

Perusal of the data revealed that the treatments had significant influence on Fe content in shoot both at fifty per cent flowering stage and at final harvest stage (Table 44). At fifty per cent flowering stage, T_8 (biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP) registered the significantly superior value of 750.30 mg kg^{-1}, followed by T_4 (726.50 mg kg^{-1}) which received biochar @ 30 t ha^{-1} + NPK as per POP and the lowest value of. POP recorded the lowest value of 340.10 mg kg^{-1}.

At final harvest stage also, there was significant difference between the treatments. Fe content in shoot was slightly lesser compared to the value registered at fifty per cent flowering stage. T_8 (biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP) recorded the superior value of 674.90 mg kg^{-1}, followed by T_4 (644.80 mg kg^{-1}) which received biochar @ 30 t ha^{-1} + NPK as per POP and the lowest value of 311.9 mg kg^{-1} was recorded by the treatment to which POP was applied.

4.3.4.1. 8. Manganese

It had been statistically observed that the treatments had significant influence on Mn content in shoot both at fifty per cent flowering stage and at final harvest stage (Table 44). At fifty per cent flowering stage, the superior value of 654.40 mg kg^{-1} was registered by T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP recorded, followed by T_4 (578.4 mg kg^{-1}) which received biochar @ 30 t ha^{-1} + NPK as per POP and the lowest value of 343.00 mg kg^{-1} was recorded by the treatment that received POP.

Table 44. **Effect of treatments on Fe, Mn, Zn and Cu content in shoot at fifty per cent flowering and final harvest stages, mg kg^{-1}**

Treatments	Fifty per cent flowering				Final harvest			
	Fe	Mn	Zn	Cu	Fe	Mn	Zn	Cu
T_1	340.10	518.48	22.39	4.02	311.90	446.26	21.34	3.96
T_2	460.20	586.29	25.02	4.96	384.60	484.93	24.17	4.84
T_3	659.20	623.68	30.73	5.54	569.30	463.60	27.97	5.20
T_4	726.50	654.40	37.66	8.21	644.80	554.70	33.95	6.74
T_5	515.70	487.30	28.02	5.19	497.60	512.78	25.38	5.06
T_6	489.70	586.50	25.08	5.11	412.50	446.25	22.87	4.92
T_7	686.70	496.60	32.84	6.04	597.40	472.90	29.19	5.79
T_8	750.30	654.40	37.84	8.35	674.90	562.80	34.00	7.05
T_9	704.80	533.80	33.05	6.34	617.60	510.10	29.53	6.15
CD (0.05)	5.697	0.878	0.260	0.129	1.746	1.103	0.110	0.066

Treatments

T_1 Package of Practices Recommendation (KAU)

T_2 Biochar @ 10 t ha^{-1} + NPK as per POP

T_3 Biochar @ 20 t ha^{-1} + NPK as per POP

T_4 Biochar @ 30 t ha^{-1} + NPK as per POP

T_5 Biochar @ 20 t ha^{-1} + 75 per cent NPK as per POP

T_6 Biochar @ 10 t ha^{-1} + FYM @ 10 t ha^{-1} + 75 per cent NPK as per POP

T_7 Biochar @ 10 t ha^{-1} + vermicompost @ 5 t ha^{-1} + 75 per cent NPK as per POP

T_8 Biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP

T_9 Biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP

The data analysis there was significant difference between the treatments. There observed a decrease in the value of Mn content than that observed at fifty per cent flowering stage. The significantly superior value of 562.80 mg kg^{-1} was T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP recorded, followed by T_4 (554.70 mg kg^{-1}) and the lowest value of 446.26 mg kg^{-1} was recorded by the treatment that received POP.

4.3.4.1. 9. Zinc

Perusal of the data revealed that application of biochar had significant influence on Zn content in shoot both at fifty per cent flowering stage and at final harvest stage (Table 44). At fifty per cent flowering stage, T_8 recorded the significantly superior value 37.84 mg kg^{-1}, which was found to be on par with T_4 (37.66 mg kg^{-1}) to which biochar was applied @ 30 t ha^{-1} along with NPK as per POP. POP registered the lowest value of T_1 22.39 mg kg^{-1}.

At final harvest stage also, the same trend was observed and there was slight decrease in the Zn content at final harvest stage than that at fifty per cent flowering stage. T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP recorded superior value of 34.00 mg kg^{-1}, which was on par with T_4 (33.95 mg kg^{-1}) which received biochar @ 30 t ha^{-1} + NPK as per POP. The lowest value was observed for treatment that received POP (21.34 mg kg^{-1}).

4. 3.4.1. 10. Copper

It is clear from the data Cu content in shoot was significantly influenced by the treatments both at fifty per cent flowering stage and at harvest stage (Table 44). At fifty per cent flowering stage, T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP recorded the superior value of 8.35 mg kg^{-1}, followed by T_4 (8.21 mg kg^{-1}) which received biochar @ 30 t ha^{-1} + NPK as per POP and the lowest value of 4.02 mg kg^{-1} was shown by the treatment that received POP.

The data analysis showed that there was significant difference between the treatments. There observed a decrease in the value of Cu content in shoot at fifty per cent flowering stage than that observed at fifty per cent flowering stage. The significantly superior value of 7.05 mg kg^{-1} was recorded by T_8 (biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP), followed by T_4 (6.74 mg kg^{-1}) which received biochar @ 30 t ha^{-1} + NPK as per POP. The lowest value of 3.96 mg kg^{-1} was recorded by the treatment that received POP.

4.3.4.2. Pod Analysis

4. 3. 4. 2. 1. Nitrogen

Treatments had significant influence on N content in pod at fifty per cent flowering stage and at final harvest stage (Table 45). At fifty per cent flowering stage, T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP recorded the significantly superior value of 3.43 per cent, followed by T_4 (3.20 per cent) to which biochar was applied @ 30 t ha^{-1} along with NPK as per POP. The lowest value was observed for POP (2.30 per cent).

At final harvest stage also, the same trend was observed and there was slight decrease in N content in pod at final harvest stage that at fifty per cent flowering stage. The significantly superior value of 3.00 per cent was registered for T_8 to which biochar was applied @ 20 t ha^{-1} along with 2 per cent PGPR and NPK as per POP, followed by T_4 (2.89 per cent) which received biochar @ 30 t ha^{-1} + NPK as per POP. The lowest value of 2.12 per cent was observed for T_1 which received POP (control).

4. 3. 4. 2. 2. Phosphorus

Statistical analysis of the data revealed that application of biochar had significant influence on the treatments at fifty per cent flowering and at final harvest stage of the crop (Table 45). T_9 which received biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP recorded the significantly superior value of 0.479 per cent and it was on par with T_8 (0.474 per cent) to which biochar was

Table 45. Effect of treatments on N, P and K content in pod at fifty per cent flowering and final harvest stages, per cent.

Treatments	Fifty per cent flowering			Final harvest		
	N	P	K	N	P	K
T_1	2.30	0.196	1.15	2.12	0.187	1.07
T_2	2.56	0.296	1.25	2.30	0.265	1.23
T_3	2.74	0.450	1.66	2.54	0.433	1.47
T_4	3.20	0.470	2.22	2.89	0.450	1.54
T_5	2.67	0.397	1.64	2.47	0.374	1.47
T_6	2.60	0.389	1.46	2.32	0.360	1.24
T_7	3.00	0.464	1.76	2.63	0.446	1.49
T_8	3.43	0.474	2.19	3.00	0.452	1.66
T_9	3.16	0.479	2.19	2.70	0.456	1.62
CD (0.05)	0.052	0.005	0.035	0.056	0.004	NS

Treatments

T_1 Package of Practices Recommendation (KAU)

T_2 Biochar @ 10 t ha^{-1} + NPK as per POP

T_3 Biochar @ 20 t ha^{-1} + NPK as per POP

T_4 Biochar @ 30 t ha^{-1} + NPK as per POP

T_5 Biochar @ 20 t ha^{-1} + 75 per cent NPK as per POP

T_6 Biochar @ 10 t ha^{-1} + FYM @ 10 t ha^{-1} + 75 per cent NPK as per POP

T_7 Biochar @ 10 t ha^{-1} + vermicompost @ 5 t ha^{-1} + 75 per cent NPK as per POP

T_8 Biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP

T_9 Biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP

applied @ 20 t ha^{-1} along with 2 per cent PGPR and NPK as per POP, followed by T_4 (0.470 per cent) which received biochar @ 30 t ha^{-1} + NPK as per POP and the lowest value of 0.196 per cent was recorded by the POP treatment.

There was significant difference between the treatments at final harvest stage also, regarding P content in pod. There observed a decrease in the value of P content than that observed at fifty per cent flowering stage. T_9 which received biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP recorded the superior value of 0.456 per cent which was on par with T_8 (0.452 per cent) which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP, followed by T_4 (0.450 per cent) which received biochar @ 30 t ha^{-1} + NPK as per POP and the lowest value of 0.187 per cent was recorded by POP. .

4. 3. 4. 2. 3. Potassium

Statistical analysis of the data indicated that treatments had significant influence on K content in pod (Table 45) both at fifty per cent flowering and at final harvest stage of the crop. T_4 which received biochar @ 30 t ha^{-1} + NPK as per POP recorded the superior value of 2.22 per cent and it was on par with T_8 (2.19 per cent) which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP and T_9 (2.19 per cent) which received biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP and the lowest value of 1.15 per cent was recorded by the treatment that received POP..

At final harvest stage also, there was no significant difference between the treatments. There observed a decrease in the value of K content than that observed at fifty per cent flowering stage. T_4 which received biochar @ 30 tha^{-1} + NPK as per POP recorded the superior value of 1.66 per cent, followed by T_9 (1.62 per cent) which received biochar @ 20 tha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP and the lowest value of 1.07 per cent was recorded by the treatment that received POP.

4. 3. 4. 2. 4. *Calcium*

It had been statistically observed that application of treatments had significant influence on pod Ca content at fifty per cent flowering stage and at final harvest stage (Table 46). At fifty per cent flowering stage, T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP recorded superior value of 2.32 per cent and it was on par with T_4 (2.28 per cent) which received biochar @ 30 tha^{-1} + NPK as per POP, followed by T_9 (1.89 per cent) which received biochar @ 20 tha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP. The lowest value was observed for T_1 (1.18 per cent).

At final harvest stage also, the same trend observed and there was slight decrease in Ca content at final harvest stage than that observed at fifty per cent flowering stage. T_8 which received biochar @ 20 tha^{-1} + 2 per cent PGPR + NPK as per POP and T_4 which received biochar @ 30 tha^{-1} + NPK as per POP it observed to be on par with pod Ca content of 1.45 per cent. This was also found to be on par with T_6 (1.43 per cent) which received biochar @ 10 t ha^{-1} + FYM @ 10 t ha^{-1}+ 75per cent NPK as per POP and T_7 (1.42 per cent) which received biochar @ 10 t ha^{-1} + vermicompost @ 5 t ha^{-1} + 75 per cent NPK as per POP. The lowest value was observed for T_1 (1.04 per cent).

4. 3. 4. 2. 5. *Magnesium*

Statistical analysis of the data indicated that treatments had significant influence on Mg content in pod (Table 46) both at fifty per cent flowering and at final harvest stage of the crop. At fifty per cent flowering stage, T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP recorded the superior value of 0.296 per cent; followed by T_4 (0.282 per cent) which received biochar @ 30 t ha^{-1} + NPK as per POP and the lowest value of 0.197 per cent was recorded by the treatment that received POP..

At final harvest stage also, there was significant difference between the treatments. There observed a decrease in the value of Mg content than that

Table 46. Effect of treatments on Ca, Mg and S content in pod at fifty per cent flowering and final harvest stages, per cent.

Treatments	Fifty per cent flowering			Final harvest		
	Ca	Mg	S	Ca	Mg	S
T_1	1.18	0.197	0.116	1.04	0.183	0.109
T_2	1.21	0.204	0.118	1.08	0.200	0.112
T_3	1.73	0.236	0.155	1.29	0.227	0.119
T_4	2.28	0.282	0.178	1.45	0.275	0.176
T_5	1.44	0.221	0.137	1.26	0.318	0.126
T_6	1.19	0.218	0.133	1.43	0.213	0.115
T_7	1.82	0.249	0.136	1.42	0.238	0.175
T_8	2.32	0.296	0.187	1.45	0.285	0.179
T_9	1.89	0.267	0.163	1.23	0.258	0.176
CD (0.05)	0.045	0.004	0.003	0.030	0.004	0.005

Treatments

T_1 Package of Practices Recommendation (KAU)

T_2 Biochar @ 10 t ha^{-1} + NPK as per POP

T_3 Biochar @ 20 t ha^{-1} + NPK as per POP

T_4 Biochar @ 30 t ha^{-1} + NPK as per POP

T_5 Biochar @ 20 t ha^{-1} + 75 per cent NPK as per POP

T_6 Biochar @ 10 t ha^{-1} + FYM @ 10 t ha^{-1} + 75 per cent NPK as per POP

T_7 Biochar @ 10 t ha^{-1} + vermicompost @ 5 t ha^{-1} + 75 per cent NPK as per POP

T_8 Biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP

T_9 Biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP

observed at fifty per cent flowering stage in the pod. T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP recorded the superior value of 0.285 per cent, followed by T_4 (0.275 per cent) and the lowest value of 0.183 per cent was recorded by the treatment that received POP.

4. 3. 4. 2. 6. *Sulphur*

Perusal of the data revealed that treatments had significant influence on the content of S in pod both at fifty per cent flowering stage and at harvest stage (Table 46). At fifty per cent flowering stage, T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP recorded the superior value of 0.187 per cent, followed by T_4 (0.178 per cent) which received biochar @ 30 t ha^{-1} + NPK as per POP and the lowest value of 0.116 per cent was recorded by the treatment that received POP..

At final harvest stage also, there was significant difference between the treatments. There observed a decrease in the value of S content than that observed at fifty per cent flowering stage. T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP recorded the superior value of 0.179 per cent , followed by T_4 (0.176 per cent) which received biochar @ 30 t ha^{-1} + NPK as per POP, T_9 (0.176 per cent) which received biochar @ 20 tha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP and T_7 (0.175 per cent) which received biochar @ 10 t ha^{-1} + vermicompost @ 5 t ha^{-1} + 75 per cent NPK as per POP and all these treatments were found to be on par. The lowest value of 0.109 per cent was recorded by the treatment that received POP.

4. 3. 4. 2. 7. *Iron*

Statistical analysis of the data indicated that the treatments had significant influence on Fe content in pod both at fifty per cent flowering stage and at final harvest stage (Table 47). At fifty per cent flowering stage, T_8 which received biochar @ 20 tha^{-1} + 2 per cent PGPR + NPK as per POP recorded the superior value of 392.70 mg kg^{-1}, followed by T_4 (385.90 mg kg^{-1}) which received biochar

Table 47. Effect of treatments on Fe, Mn, Zn and Cu content in pod at fifty per cent flowering and final harvest stages, mg kg^{-1}

Treatments	Fifty per cent flowering stage				Final harvest stage			
	Fe	Mn	Zn	Cu	Fe	Mn	Zn	Cu
T_1	152.40	134.60	19.51	3.97	128.80	100.40	18.25	3.84
T_2	196.70	156.20	22.46	4.75	173.10	120.00	19.28	4.69
T_3	243.60	212.40	28.37	5.28	220.00	152.80	25.19	5.15
T_4	385.90	254.60	34.61	6.86	362.30	202.40	30.65	6.63
T_5	235.40	198.60	25.03	5.13	211.80	133.30	22.23	5.02
T_6	212.60	177.90	23.26	5.08	189.00	126.70	20.20	4.85
T_7	252.90	225.50	29.18	5.98	229.30	165.70	25.74	5.74
T_8	392.70	264.90	34.74	7.02	369.10	219.60	30.74	7.00
T_9	360.10	231.90	29.83	6.25	336.50	182.30	27.35	6.09
CD (0.05)	0.865	1.049	0.325	0.310	1.419	1.054	0.165	0.155

Treatments

T_1 Package of Practices Recommendation (KAU)

T_2 Biochar @ 10 t ha^{-1} + NPK as per POP

T_3 Biochar @ 20 t ha^{-1} + NPK as per POP

T_4 Biochar @ 30 t ha^{-1} + NPK as per POP

T_5 Biochar @ 20 t ha^{-1} + 75 per cent NPK as per POP

T_6 Biochar @ 10 t ha^{-1} + FYM @ 10 t ha^{-1} + 75 per cent NPK as per POP

T_7 Biochar @ 10 t ha^{-1} + vermicompost @ 5 t ha^{-1} + 75 per cent NPK as per POP

T_8 Biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP

T_9 Biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP

@ 30 t ha^{-1} + NPK as per POP and the lowest value of 134.6 mg kg^{-1} was recorded by the treatment that received POP.

At final harvest stage also, there was significant difference between the treatments. There observed a decrease in the value of Fe content than that observed at fifty per cent flowering stage. T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP recorded the superior value of 369. 10 mg kg^{-1}, followed by T_4 (362.30 mg kg^{-1}) which received biochar @ 30 t ha^{-1} + NPK as per POP and the lowest value of 128.80 mg kg^{-1} was recorded by the treatment that received POP.

4. 3. 4. 2. 8. *Manganese*

It had been statistically observed that the treatments had significant influence on Mn content in pod both at fifty per cent flowering stage and at final harvest stage (Table 46). At fifty per cent flowering stage, T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP recorded the superior value of 264.90 mg kg^{-1}, followed by T_4 (254.60 mg kg^{-1}) which received biochar @ 30 t ha^{-1} + NPK as per POP and the lowest value of 134.60 mg kg^{-1} was recorded by the treatment that received POP.

At final harvest stage also, there was significant difference between the treatments. There observed a decrease in the value of Mn content than that observed at fifty per cent flowering stage. T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP recorded the superior value of 219.60 mg kg^{-1}, followed by T_4 (202.40 mg kg^{-1}) which received biochar @ 30 t ha^{-1} + NPK as per POP and the lowest value of 100.40 mg kg^{-1} was recorded by the treatment that received POP.

4. 3. 4. 2. 9. Zinc

It had been statistically observed that application of treatments had significant influence on Zn content in pod at fifty per cent flowering stage and at final harvest stage (Table 47). At fifty per cent flowering stage, T_8 which received biochar @ 20 tha^{-1} + 2 per cent PGPR + NPK as per POP recorded superior value 34.74 mg kg^{-1} and it was on par with T_4 (34.61 mg kg^{-1}) which received biochar @ 30 t ha^{-1} + NPK as per POP. The lowest value was observed for T_1 (19.51 mg kg^{-1}).

At final harvest stage also, the same trend observed and there was slight decrease in N content at final harvest stage that at fifty per cent flowering stage. T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP recorded superior value of 30.74 mg kg^{-1}, followed by T_4 (30.65 mg kg^{-1}). The lowest value was observed for treatment that received POP (18.25 mg kg^{-1}).

4. 3. 4. 2. 10. Copper

It was clear from the data that treatments had significant influence on the content of Cu in pod both at fifty per cent flowering stage and at harvest stage (Table 47). At fifty per cent flowering stage, T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP recorded the superior value of 7.02 mg kg^{-1}, followed by T_4 (6.86 mg kg^{-1}) which received biochar @ 30 t ha^{-1} + NPK as per POP and the lowest value of 3.97 mg kg^{-1} was recorded by the treatment that received POP..

At final harvest stage also, there was significant difference between the treatments. There observed a decrease in the value of Cu content than that observed at fifty per cent flowering stage. T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP recorded the superior value of 7.00 mg kg^{-1}, followed by T_4 (6.63 mg kg^{-1}) which received biochar @ 30 t ha^{-1} + NPK as per POP and the lowest value of 3.84 mg kg^{-1} was recorded by the treatment that received POP.

4. 3. 4. 3. Total Uptake of Nutrients

The data on effect of treatments on total uptake of nutrients are presented in Table 48 and Table 49.

4. 3. 4. 3. 1. Nitrogen

A perusal of the data revealed that there was significant difference between the treatments (Table 48). The highest N uptake of 105.50 kg ha^{-1} was recorded by the treatment that received T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP followed byT_4 (93.19 kg ha^{-1}) which received biochar @ 30 tha^{-1} + NPK as per POP. The lowest value of 51.19 kg ha^{-1} was recorded by the control treatment.

4. 3. 4. 3. 2. Phosphorus

It had been statistically verified that the treatments had significant influence on P uptake (Table 48). Treatment that received T_8 (biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP) recorded significantly superior value of 14.17 kg ha^{-1}, followed by T_9 (13.22 kg ha^{-1}) to which biochar was applied @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP and T_4 (12.99 kg ha^{-1}) which received biochar @ 30 t ha^{-1} + NPK as per POP. The lowest value of 4.73 kg ha^{-1} was recorded by treatment that received POP.

4. 3. 4. 3. 3. Potassium

Statistical analysis of the data indicated that there was significant difference between the treatments (Table 48). T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP registered the significantly superior value of 62.85 kg ha^{-1} and it was followed by T_8 (56.59 kg ha^{-1}) that received biochar @ 30 t ha^{-1} + NPK as per POP and then by T_9 (56.12 kg ha^{-1}). The lowest K uptake of 26.74 kg ha^{-1} was shown by the control treatment.

Table 48. Effect of treatments on total uptake of N, P, K, Ca, Mg and S, kg ha^{-1}

Treatments	N	P	K	Ca	Mg	S
T_1	51.19	4.73	26.74	26.73	4.77	3.28
T_2	66.41	7.55	35.46	32.76	6.61	4.76
T_3	79.00	11.83	50.87	48.86	7.70	5.48
T_4	93.19	12.99	56.59	56.54	9.42	7.36
T_5	75.38	10.32	49.62	42.47	9.48	5.30
T_6	69.00	9.70	40.48	42.71	7.02	4.86
T_7	82.42	12.30	52.17	52.33	8.06	6.82
T_8	105.50	14.17	62.85	61.03	10.67	7.99
T_9	85.85	13.22	56.12	49.47	8.70	6.99
CD (0.05)	4.042	0.190	2.807	3.526	0.418	0.235

Treatments

T_1 Package of Practices Recommendation (KAU)

T_2 Biochar @ 10 t ha^{-1} + NPK as per POP

T_3 Biochar @ 20 t ha^{-1} + NPK as per POP

T_4 Biochar @ 30 t ha^{-1} + NPK as per POP

T_5 Biochar @ 20 t ha^{-1} + 75 per cent NPK as per POP

T_6 Biochar @ 10 t ha^{-1} + FYM @ 10 t ha^{-1} + 75 per cent NPK as per POP

T_7 Biochar @ 10 t ha^{-1} + vermicompost @ 5 t ha^{-1} + 75 per cent NPK as per POP

T_8 Biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP

T_9 Biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP

4. 3. 4. 3. 4. Calcium

Regarding this parameter, there was significant difference between the treatments (Table 48). T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP recorded the maximum value of 61.03 kg ha^{-1} followed by T_4 (56.54 kg ha^{-1}) which received biochar @ 30 t ha^{-1} + NPK as per POP. The lowest uptake of 26.73 kg ha^{-1} was registered by the treatment that received POP.

4. 3. 4. 3. 5. Magnesium

The data showed that, uptake of Mg also was significantly influenced by the treatments (Table 48). T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP recorded the significantly superior value for Mg uptake (10.67 kg ha^{-1}) followed by T_5 (9.48 kg ha^{-1}) which received biochar @ 20 t ha^{-1} + 75 per cent NPK as per POP and the lowest value of 4.77 kg ha^{-1} was recorded by the control treatment.

4. 3. 4. 3. 6. Sulphur

A perusal of the data revealed that there was significant difference between the treatments (Table 48). The highest S uptake of 7.99 kg ha^{-1} was recorded by the treatment that received T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP, followed by T_4 (7.36 kg ha^{-1}) which received biochar @ 30 t ha^{-1} + NPK as per POP. The lowest value of 3.28 kg ha^{-1} was recorded by the control treatment.

4. 3. 4. 3. 7. Iron

It is clear from the data that there was significant difference between the treatments (Table 49). The highest Fe uptake of 1623.00 g ha^{-1} was recorded by the treatment that received T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP, followed by T_4 (1480.01 g ha^{-1}) which received biochar

Table 49. Effect of treatments on total uptake of Fe, Mn, Zn and Cu, g ha^{-1}

Treatments	Fe	Mn	Zn	Cu
T_1	482.63	559.31	47.79	9.58
T_2	708.42	697.58	61.25	13.92
T_3	1027.72	780.36	81.35	16.13
T_4	1480.01	1028.04	103.89	21.84
T_5	928.57	777.45	71.50	15.49
T_6	778.26	684.05	62.89	14.56
T_7	1083.02	823.13	84.34	18.11
T_8	1623.00	1140.50	111.09	24.52
T_9	1358.07	911.72	89.67	19.54
CD (0.05)	26.909	39.951	7.692	1.210

Treatments

T_1 Package of Practices Recommendation (KAU)

T_2 Biochar @ 10 t ha^{-1} + NPK as per POP

T_3 Biochar @ 20 t ha^{-1} + NPK as per POP

T_4 Biochar @ 30 t ha^{-1} + NPK as per POP

T_5 Biochar @ 20 t ha^{-1} + 75 per cent NPK as per POP

T_6 Biochar @ 10 t ha^{-1} + FYM @ 10 t ha^{-1} + 75 per cent NPK as per POP

T_7 Biochar @ 10 t ha^{-1} + vermicompost @ 5 t ha^{-1} + 75 per cent NPK as per POP

T_8 Biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP

T_9 Biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP

@ 30 t ha^{-1} + NPK as per POP. The lowest value of 482.63 g ha^{-1} was recorded by the control treatment.

4. 3. 4. 3. 8. Manganese

Regarding this parameter, there was significant difference between the treatments (Table 49). T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP recorded the maximum value of 1140.50 g ha^{-1} followed by T_4 (1028.04 g ha^{-1}). The lowest uptake of 559.31 g ha^{-1} was registered by the treatment that received POP.

4. 3. 4. 3. 9. Zinc

Statistical analysis of the data indicated that there was significant difference between the treatments (Table 49). T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP registered the significantly highest value of 111.09 g ha^{-1} and it was followed by T_4 (103.89 g ha^{-1}) which received biochar @ 30 t ha^{-1} + NPK as per POP. The lowest Zn uptake of 47.79 g ha^{-1} was shown by the control treatment.

4. 3. 4. 3. 10. Copper

It had been statistically verified that the treatments had significant influence on Cu uptake (Table 49). Treatment that received T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP recorded significantly superior value of 24.52 g ha^{-1}, followed by T_4 (21.84 g ha^{-1}) which received biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP. The lowest value of 9.58 g ha^{-1} was recorded by treatment that received POP.

4. 3. 5. Scoring for Incidence of Pests and Diseases

No severe pest and disease incidence was noticed during the period of crop growth. To prevent pod borer infestation, Ekalux 0.20 per cent was sprayed and

Copper oxychloride @ 4g l^{-1} was drenched to manage basal rot. There was no variation among the treatments in the occurrence of disease.

4. 3. 6. Cost of Production of Biochar

Table 50. Cost of production of biochar

Particulars	Cost (Rs./t)
Initial cost	
Production unit	3000/-
Labour cost	
a) Production of biochar	5500/-
b) Grinding and sieving	2500/-
Transportation	1500/-
Total cost	12, 500/-

Hence, the production of biochar from tender coconut husk is one of the best ways to utilize the biowaste which may otherwise accumulate in the roadsides causing soil and water pollution. The biochar produced by the process of slow pyrolysis had good physical and chemical properties with alkaline pH, high CEC, improved WHC, better SSA, micropore area and micropore volume. Tender coconut husk biochar is a highly carbonaceous material and rich source of all the nutrients needed for crop growth.

The desorption experiments revealed that biochar could desorb 3380 mg NH_4^+, 2858.43 mg PO_4^{3-}, 10226.35 mg K^+, 1840 mg Ca^{2+}, 680 mg Mg^{2+}, 2019.87 mg SO_4^{2-}, 45.16 mg Fe^{2+}, 94.66 mg Mn^{2+}, 5.62 mg Zn^{2+}, 1.06 mg Cu^{2+} within 3 days when it was equilibrated with de-ionised water in 1: 100 ratio and hence biochar is a good and slow releaser of nutrients that are needed for plant growth.

Application of biochar to soil reduces CO_2 emission substantially, compared to other organic amendments like FYM and vermicompost. Use of tender coconut husk biochar improves all the soil properties like WHC, per cent

Water Stable Aggregates, porosity, pH, EC, CEC, available nutrient status, and lowers bulk density to favour better crop yields. The nutrient content in plants and pods and the uptake of nutrients by the crop were increased by the application of biochar. All these factors contributed for improving the number and weight of nodules per plant, pod yield, better Harvest Index and B: C ratio in yard long bean variety Vellayani Jyothika.

Discussion

5. DISCUSSION

The detailed investigations on production and characterization of biochar, laboratory experiments *viz.* nutrient sorption- desorption studies; carbon dioxide emission studies and field experiment were carried out at College of Agriculture, Vellayani to characterize biochar from tender coconut husk and to assess its effects on soil properties, growth and yield of yard long bean (*Vigna unguiculata* subsp. *sesquipedalis*) as the test crop. Biochar was produced by the fabricated apparatus (biochar kiln) by the process of slow pyrolysis, it was characterized and tested in the field at different levels of application *viz.* 10, 20 and 30 t ha^{-1} using yard long bean, variety Vellayani Jyothika as the test crop during January to April 2013. Along with biochar, other commonly used organic manures *viz.* FYM and vermicompost; biofertilizers *viz.* PGPR and AMF were also tested in the field. A critical analysis of the results of the experiment revealed marked response of the crop to biochar application. The salient findings generated from the present study are discussed in the light of published information and fundamental theoretical knowledge.

5.1. CHARACTERIZATION OF BIOCHAR

Physical and chemical properties of biochar were analyzed and chemical properties were compared with that of raw material. Tender coconut husk biochar is a good source of all the nutrients. The biochar produced had an alkaline pH, high CEC, WHC, SSA and lower bulk density. The EC and CEC of the produced biochar were 1.73 dS m^{-1} and 15.26 cmol (+) kg^{-1} respectively. The total C content was 72.30 per cent indicating the fact that tender coconut husk biochar is highly carbonaceous in nature. The biochar was rich in nutrients with N content of 1.05 per cent, P content of 0.38 per cent, K content of 2.27 per cent, Ca content of 0.40 per cent, Mg content of 0.29 per cent, S content of 0.27 per cent, Fe content of 123.04 mg kg^{-1}, Mn content of 16.50 mg kg^{-1}, Zn content of 21.09 mg kg^{-1} and Cu content of 3.98 mg kg^{-1}. The C: N ratio of tender coconut husk biochar was 68.86, which was slightly higher than that of raw tender coconut husk (66.52).

While converting the raw tender coconut husk into biochar, the volume was reduced and this may be the reason for improved nutrient concentration in biochar, compared to that of raw material.

The biochar produced was alkaline in nature with a pH of 9.13. The high pH of biochar was due to the increased concentration of alkaline metal (Ca^{2+}, Mg^{2+}, and K^{+}) oxides present in biochar (Steiner *et al.*, 2007). This is in conformity with the results obtained by Sukartono *et al.* (2011) and Shenbagavalli and Mahimairaja (2012) where the biochar produced from coconut shell had pH of 9.18 and 9.90 respectively. Wiedner *et al.* (2013) characterized biochar produced from poplar tree biomass and wheat straw and obtained a pH of 9.96 and 9.70 respectively. Similarly, Major *et al.* (2010a) produced and characterized wood biochar with a pH of 9.20 to evaluate its effect on maize nutrition. Jien and Wang (2013) also characterized wood biochar and reported that the produced biochar was alkaline in nature with a pH of 9.90.

The CEC of tender coconut husk biochar produced in the experiment was 15.26 cmol kg^{-1} .This is in compliance with the results obtained by Sukartono *et al.* (2011) who characterized biochars produced from coconut shell and cattle dung ($200^{0}C$-$330^{0}C$) and reported a CEC of 11.78 and 16.79 cmol kg^{-1} respectively. Major *et al.* (2010a) reported that wood biochar had CEC of 11.19 cmol kg^{-1} whereas Slavich *et al.* (2013) revealed that the biochar produced from cattle manure by pyrolysis at a highest treatment temperature of 550°C had CEC of 13.00 cmol kg^{-1}.

The high CEC of the biochar is primarily attributed to the formation of graphene structure during the process of pyrolysis. Graphene is a polyaromatic structure: a flat monolayer of C atoms that presents high indices of stability, breaking strength and electrical conductivity (Geim and Novoselov, 2007). As temperature increases in the pyrolysis range, ordering of graphene sheets occurs. Biochars produced above 350°C are dominated by aromatic C groups and a range of different functional groups exist on the surfaces of the graphene sheets. H, N, O, P and S are incorporated in the aromatic rings and determine the electronegativity of the biochar, influencing its CEC. The fact that its entire volume is exposed to its surrounding makes it very efficient to adsorb molecules. The increased formation of carboxylic and phenolic functional groups and adsorption sites on surfaces and within pores of biochar by ageing could also influence it's CEC (Cheng *et al.*, 2006; Liang *et al.*, 2006) and, consequently, the capacity of biochar to form complexes with metal ions and to adsorb nutrients.

Elevated CEC of biochar is due to the increase in charge density per unit surface of organic matter, which equates with a greater degree of oxidation, or increases in surface area for cation adsorption, or a combination of both. Liang *et al.* (2006) reported that, as a consequence of surface oxidation of black carbon particles, the adsorption of organic matter and its charge density (CEC per unit surface area) were increased in anthrosols.

The C: N ratio of biochar was 68.86 and it was comparable with the results obtained by Wiedner *et al.* (2013) who performed the chemical evaluation of chars produced from wheat biomass where the C:N ratio obtained was 73.70. Ameloot *et al.* (2013), while characterising biochar from swine manure and willow wood by pyrolysing the digestate at 350^{0}C, obtained a C: N ratio of 63.20.

The WHC of the produced biochar was promising (226.00 per cent). The very high WHC of biochar is attributed to the highly porous nature and elevated surface area of biochar particles. This is in conformity with the results obtained by Saranya *et al.* (2011) who characterized acacia wood based biochar and reported that the biochar produced had WHC of 200 per cent. Shenbagavalli and Mahimairaja (2012) reported that biochar from Prosopis wood had WHC of 131 per cent. Ippolito *et al.* (2012) reported that biochar addition @ 2 per cent, by weight, increased the moisture content of two Aridisols, by 3 to 7 per cent relative to control soils, and when relevant evapo-transpiration rates were considered, it was concluded that this could lead to an additional 0.40-2.50 days of available water for crop growth.

Bulk density of the produced biochar was very low (0.140 Mg m^{-3}). It indicates that the biochar produced was significantly less dense than the soil. A lower bulk density value of biochar is an indication on when added to the soil, it can increase soil porosity and thus plant available moisture. (Singer and Munns, 2006). Sukartono *et al.* (2011) reported that the biochar produced from coconut shell had bulk density of 0.710 g cm^{-3} whereas cattle dung biochar registered a value of 0.670 g cm^{-3}. Zhang *et al.* (2010) observed that the application of wheat straw biochar decreased the bulk density of a rice paddy soil @ 40 t ha^{-1}. Major *et al.* (2010a) noticed that the application of biochar @ 20 t ha^{-1} significantly reduced the density of a heavy clay soil.

In the present study, the biochar produced from tender coconut husk recorded BET surface area of 157.93 m^2 g^{-1}, Langmuir surface area of 237.81 m^2 g^{-1}, external surface area of 47.10 m^2 g^{-1}, micropore area of 110.83 m^2 g^{-1} and micropore volume of 0.06 cm^3 g^{-1}. During pyrolysis, loss of feedstock mass in the form of volatile organic compounds leaves voids, which creates an extensive pore network consisting of pores and cracks. The pore sizes distribution of biochar is highly variable and encompasses micro, meso, and macropores with internal diameters below < 2 nm, 2-50 nm, and above 50 nm, respectively (Downie *et al.*, 2009). Mainly, the micropores are formed during pyrolysis due to loss of water molecules during dehydroxylation of the biomass. The surface area and microporosity of biochar are very important physical characteristics, which are positively related to the capacity of biochars to adsorb minerals and water (Atkinson *et al.*, 2010). The pore size volume and pore size distribution of biochar has its impact on important soil parameters *viz.* water retention, nutrient retention, gas adsorption and total surface area.

Zheng *et al.* (2010) produced biochar from wood pellet at 750^0C with surface area of 105.30 m^2 g^{-1} and corn cob biochar pyrolysed at 350^0C had the SSA of 3.36 m^2 g^{-1}. Ameloot *et al.* (2013) while characterising biochar by pyrolysing the digestate at 350^0C from swine manure and willow wood, obtained surface area values of 9.02 and 15.66 mm^3 g^{-1} respectively.

The experimental results revealed that tender coconut husk biochar is highly carbonaceous, with a carbon content of 72.30 per cent. Biochar is first and foremost characterised by its high organic C content, which mainly comprises conjugated aromatic compounds of six C atoms linked together in rings. The condensed aromatic nature of biochar is what makes it so stable in the environment. The biochar structure is essentially amorphous, but may contain crystalline structures locally of highly ordered graphene sheets (Downie *et al.*, 2009). Ameloot *et al.* (2013) reported that biochar produced from swine manure at 350^0C and 700^0C reported a C content of 67.10 and 80.30 per cent respectively. The high carbon content of biochar is advantageous in terms of maximizing the amount of carbon storage (Lee *et al.*, 2013).

It is evident from the experiment that the elemental composition of biochar is superior to that of tender coconut husk and majority of the nutrients were higher in biochar compared to the raw material. The physical properties of the produced biochar were also desirable and promising. Since the pH is alkaline, biochar can be used as a soil amendment in acid soils.

5.2. LABORATORY EXPERIMENTS USING BIOCHAR

Laboratory studies were conducted at Department of Soil Science and Agricultural Chemistry, College of Agriculture, Vellayani.

5.2.1. Nutrient Sorption- Desorption Studies

5.2.1.1. Desorption of Nutrients from Biochar

Desorption experiments were performed by rinsing 1g powdered biochar with de-ionized water in 1:100 ratio. The biochar solution was shaken for 84 h and samples were drawn at 12 h intervals until the pH of the filtrate was stabilized (9.20) between two consecutive rinses.

The data on desorption of NH_4^+, PO_4^{3-} and K^+ has been illustrated in Fig. 3. Regarding desorption of NH_4^+ from biochar, 32.25 per cent (3386.25 μg g^{-1}) of the initial concentration of the nutrient was found to be desorbed within 3 days. This agrees with another study conducted by Graber *et al.* (2010) who performed water extraction of citrus wood biochar (0.60 percent N) by continually stirring biochar in water (1:10) for 30 minutes and measuring the extract for NH_4^+ (0.20 mgNH_4-N g^{-1}).

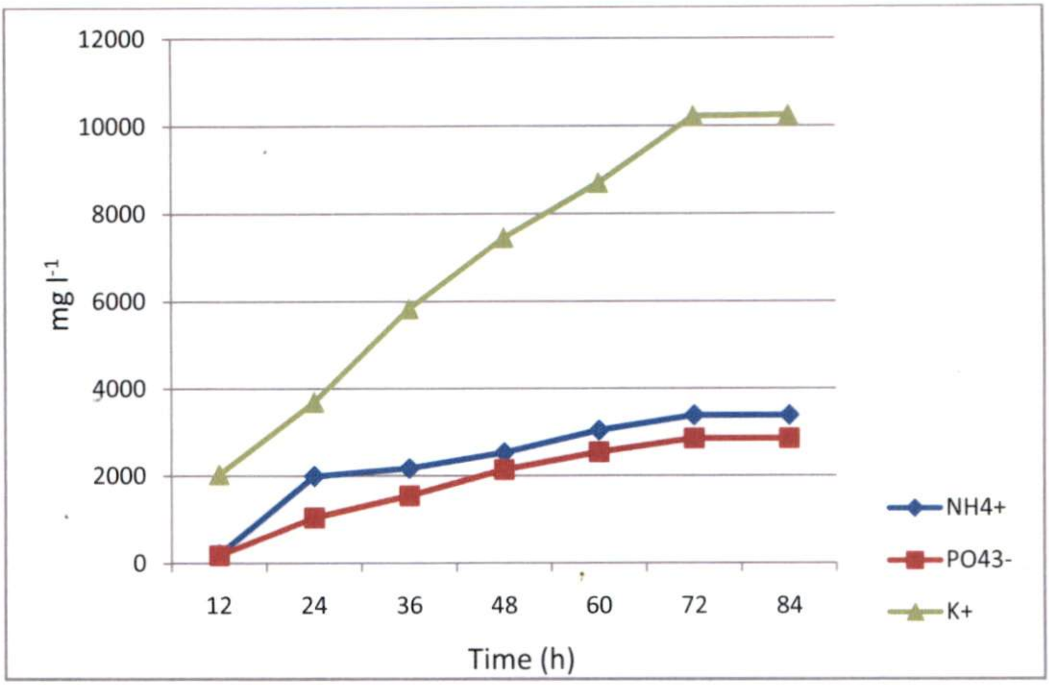


Fig. 3. Desorption of NH_4^+, PO_4^{3-} and K^+ from biochar

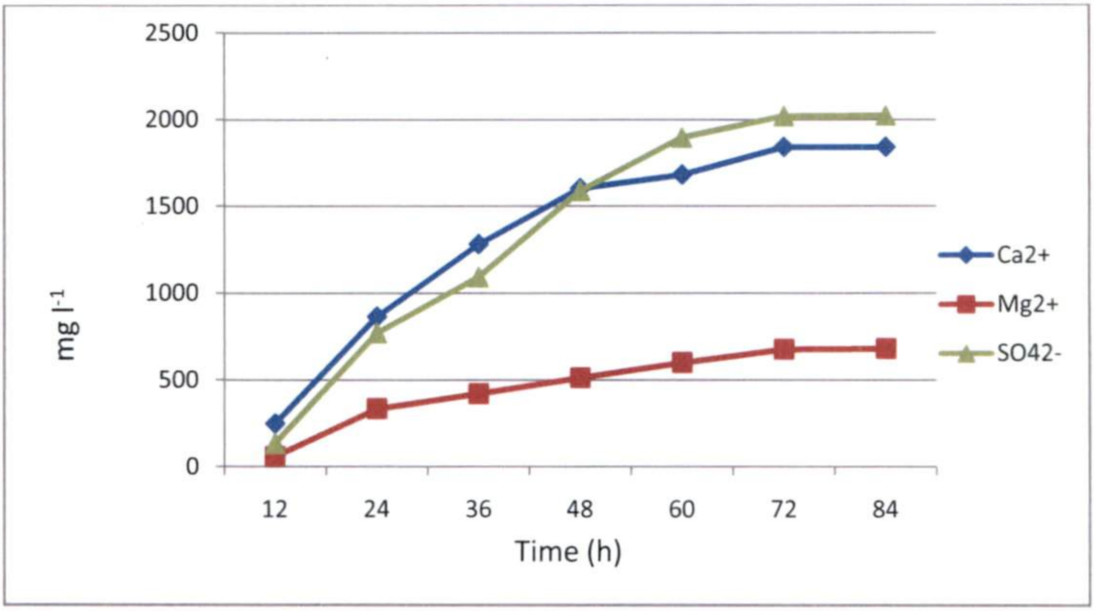


Fig. 4. Desorption of Ca^+, Mg^{2+} and SO_4^{2-} from biochar

Desorption of NO_3^- from biochar was not detected. The results are in conformity with the results obtained by Hollister (2011) who performed leaching experiments to study the desorption of NH_4^+, NO_3^- and PO_4^{3-} using corn and oak biochars produced by pyrolysis at 350° and 550° C.

The initial concentration of PO_4^{3-} on biochar was 3780 mg kg^{-1} and after 72 h, 75.62 per cent of the initial concentration was desorbed. Final concentration of PO_4^{3-} on biochar was 921.56mg kg^{-1} after 3 days. Since it is an anion easy for desorption, more PO_4^{3-} was desorbed from biochar than NH_4^+ in aqueous solutions.

As far as desorption of K^+ is concerned, the initial concentration of K^+ in biochar was 22,700 mg kg^{-1}. 10, 226.35 mg l^{-1} K^+ (45.05 per cent) was desorbed from biochar to the solution phase within 3 days. Reasonably high K content (2.27 per cent) in biochar is responsible for desorption of K^+ at a moderate rate.

It is evident from the data that within 3 days, 46 per cent (2160.00 mg kg^{-1}) of the initial concentration of Ca^{2+} (4000 mg kg^{-1}) was desorbed from biochar to the solution phase (Fig. 4). Similar results were obtained by Singh *et al.* (2010) who studied desorption of Ca from biochar made from leaf and wood material of *Eucalyptus saligna.* The reason for desorption of Ca from biochar was the high content of Ca (0.40 per cent) in tender coconut husk biochar.

Calcium oxalate is a common crystal in plant biomass (Nakata, 2003). As the feedstocks are pyrolyzed, calcium oxalate is converted to calcite (Singh *et al.*, 2010). The solubility of calcite, Log $Ksp = -6.37$ (Zeebe, 2001) is higher than that of calcium oxalate monohydrate, Log $Ksp = -8.64$. The formation of calcite at high temperature during pyrolysis should be the reason for desorption of Ca^{2+} from biochar surface (Hollister, 2011).

Regarding desorption of Mg^{2+} from biochar, 23.31 per cent of the initial concentration of Mg^{2+} was desorbed from biochar to the solution phase within 3 days The experimental results revealed that 74.28 per cent (2019.87 mg kg^{-1}) of the initial concentration of SO_4^{2-} was desorbed within 72 h. The initial concentration concentration of SO_4^{2-} on biochar surface was 2720 mg kg^{-1}. The data is presented in Fig. 4.

The initial concentration of Fe^{2+} in biochar was 123.04 mg kg^{-1} (Fig. 5). It was reduced after each rinse and finally after 3 days of rinsing, 38.80 per cent of the initial concentration of Fe^{2+} was desorbed from biochar to the solution phase (45.16 mg kg^{-1}).

From the desorption experiment, it is clear that 30.05 per cent (4.96 mg kg^{-1}) Mn^{2+} was desorbed from biochar to the solution phase within 3 days (Fig. 5). Regarding desorption of Zn^{2+}, the initial concentration of Zn^{2+} in biochar was 21.09 mg kg^{-1} and finally, 26.75 per cent (5.62 mg kg^{-1}) Zn^{2+} was desorbed from biochar to the solution phase after 3 days.

The experimental results revealed that 26.67 per cent of the initial concentration of Cu^{2+} was desorbed and the initial concentration of Cu^{2+} was 3.98 mg kg^{-1}. It was reduced after each rinse and finally it was 2.92 mg kg^{-1} after 3 days (Fig. 5).

It can be inferred from the desorption experiment that after each rinse of biochar with de-ionized water, the concentration of nutrient in the solution phase was found to be increased that resulted in a decrease in the initial concentration of the nutrient that was already present on biochar surface. pH of the rinse solution was progressed during the rinse procedure and stabilized to 9.20 after 72 h. Biochar from tender coconut husk is a rich source of all the nutrients . Because of the high SSA and micropore volume, nutrients are released until the pH gets stabilized.

With time, there observed an increase in desorption of all the nutrients. Release of anions from biochar was very high when compared to that of cations. From the results of the desorption experiment, it can be concluded that a total of 32.35 per cent NO_3^-, 75.65 per cent PO_4^{2-}, 45.14 per cent K^+, 46.00 per cent Ca^{2+}, 34.00 per cent Mg^{2+}, 74.38 per cent SO_4^{2-}, 36.80 per cent Fe^{2+}, 30.05 per cent Mn^{2+}, 26.75 per cent Zn^{2+} and 26.72 per cent Cu^{2+} were desorbed from biochar

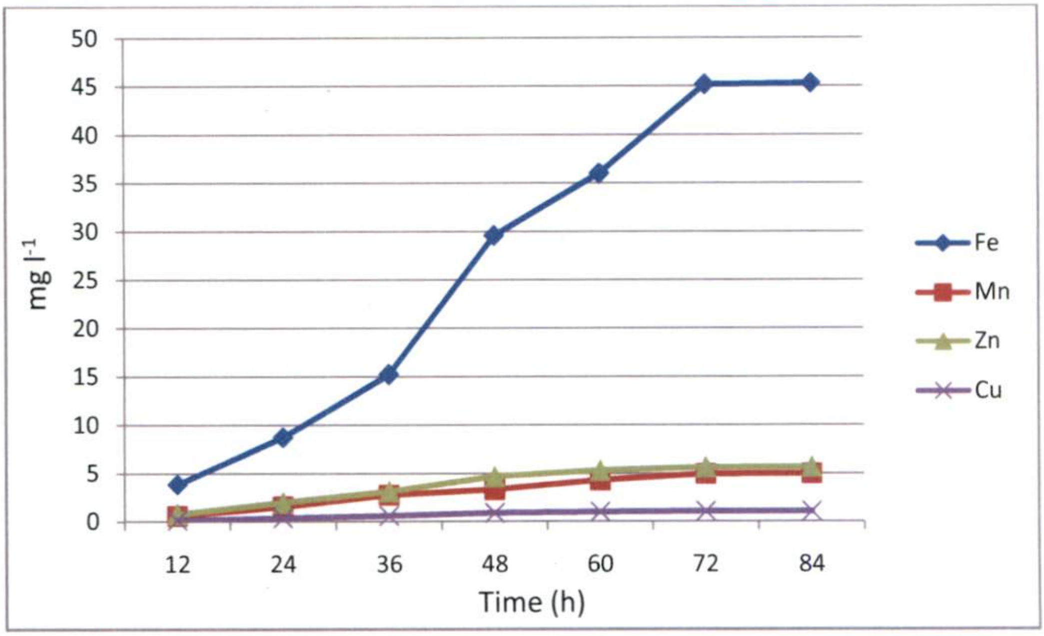


Fig.5. Desorption of Fe^{2+}, Mn^{2+}, Zn^{2+} and Cu^{2+} from biochar

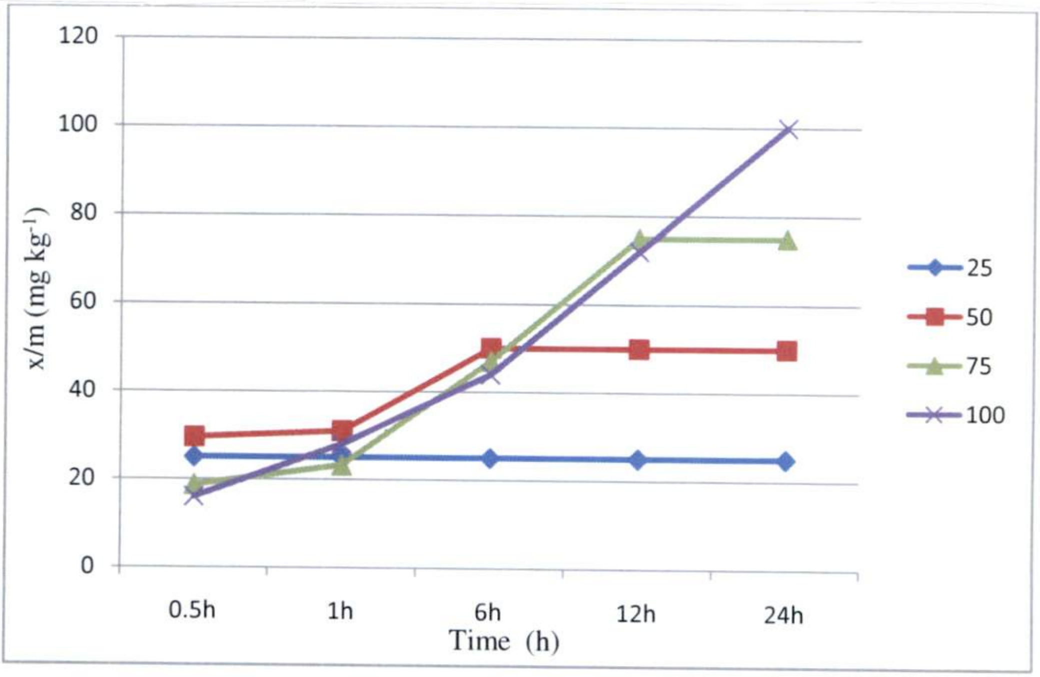


Fig. 6. Sorption of NH_4^+ on biochar

within 72 h from biochar. The extent of desorption was highest for PO_4^{3-} (75.62 per cent), followed by SO_4^{2-} (74.26 per cent). The lowest per cent of nutrients desorbed was Zn^{2+} (26.67 per cent) and Cu^{2+} (26.67 per cent). Biochar from tender coconut husk could release 3386.25 μg NH_4^+, 2858.44 μg PO_4^{3-}, 10226.35 μg K^+, 1840 μg Ca^{2+}, 676 μg Mg^{2+}, 2019.87 μg SO_4^{2-}, 45.16 μg Fe^{2+}, 94.66 μg Mn^{2+}, 5.62 μg Zn^{2+}, 1.06 μg Cu^{2+} in 72 h. Hence, biochar is a good source of nutrients, an excellent releaser of nutrients and can be used for crop production to improve crop yield.

5.2.1.2. Sorption of Nutrients on Biochar

Biochar usually has greater sorption ability than natural soil organic matter due to its greater surface area, negative surface charge, and charge density (Liang *et al.*, 2006). Charred organic matter like biochar generally sorbs 10 to 1000 times more nutrients than un-charred organic matter (Smernik, 2009). The porous nature and surface chemical properties determine the adsorptive capabilities of biochar. Biochar has been reported to sorb dissolved NH_4^+ (Lehmann *et al.*, 2003); phosphate (PO_4^{3-}) (Streubel *et al.*, 2012), and other ionic solutes (Radovic, 2000).

From the sorption experiments using tender coconut husk biochar, it was observed that with increase in equilibration time, the adsorption of all the nutrients increased.

When solutions containing graded doses of nutrients *ie,* 25, 50, 75 and 100 mgml^{-1} NH_4^+-N were provided, 100 per cent of the given nutrients were sorbed on biochar within 24 h (Fig. 6). When 25 mg ml^{-1} NH_4^+-N was equilibrated, the nutrient was sorbed completely within 1 h. A comparison of adsorption of different concentrations of nutrients within a specified period of time revealed a decrease in the adsorption of NH_4^+ with increase in concentration. Once biochar was added to the aqueous solutions, the concentrations of NH_4^+ decreased sharply within the first half hour, and then decreased gradually with increasing contact time until the maximum sorption was achieved. Sarkhot *et al.* (2012) also observed that the proportion of the NH_4^+ available in solution that was sorbed by biochar decreased with increasing solution concentration. In pure solution, 50 per cent of the available NH_4^+ was adsorbed by biochar at lower solution NH_4^+ concentrations; whereas only 7 per cent was adsorbed at higher solution concentration after one week. Zheng *et al.* (2010) concluded that biochars successfully sorbed NH_4^+ from aqueous solutions. Yao *et al.* (2011) found that biochar could sorb NH_4^+ from solution with removal rates ranging from 1.80 per cent to 15.70 per cent. The sorption capacity of the biochars for NH_4^+ was much higher than activated carbon and other previous reported sorbents such as sepiolite (0.1 mmol g^{-1}) and acid treated slag (0.0007 mmol g^{-1}) (Khelifi *et al* ., 2002).

Although the exact mechanism for NH_4^+ retention was not identified it was suggested that physical entrapment of NH_4^+ in biochar pore structures may have been responsible (Saleh *et al.*, 2012). Since NH_4^+ ion has a diameter of 286 pico meter (Spath and Konig, 2010) and there is wide range of pore sizes in biochar materials (Downie *et al.*, 2009), it is possible to sorb NH_4^+ ions on biochar. It was also suggested that as a cation, the primary sorption mechanism of NH_4^+ by negatively charged biochar is likely via an electrostatic attraction process (Lehmann, 2007).

The quantity of PO_4^{3-} sorbed on biochar was 24.17 mg kg^{-1} from 25 μg ml^{-1} solution, 49.89 mg kg^{-1} from 50 mg l^{-1}, 72.11 mg kg^{-1} from 75 mg l^{-1} and 90.70 mg kg^{-1} from 100 mg l^{-1} within 24 h (Fig. 7). When 25 mg l^{-1} PO_4^{3-} solutions were equilibrated with biochar for half an hour, it could sorb only 8.00 per cent of the ions provided. But, when the concentration was increased to 100 and equilibration time was enhanced to 24 h, 90.00 per cent of the ions were sorbed. PO_4^{3-} sorption is less compared to other cationic nutrients. However, when the equilibration time and the concentration of PO_4^{3-} were increased, there was increase in adsorption. The anion exchange capacity is low in rinsed biochar and PO_4^{3-} could be sorbed on to the biochar surface due to the concentration gradient between the bulk solution and the sorbent surface. The sorption of PO_4^{3-} from solution was a more gradual process until reaching sorption equilibrium.

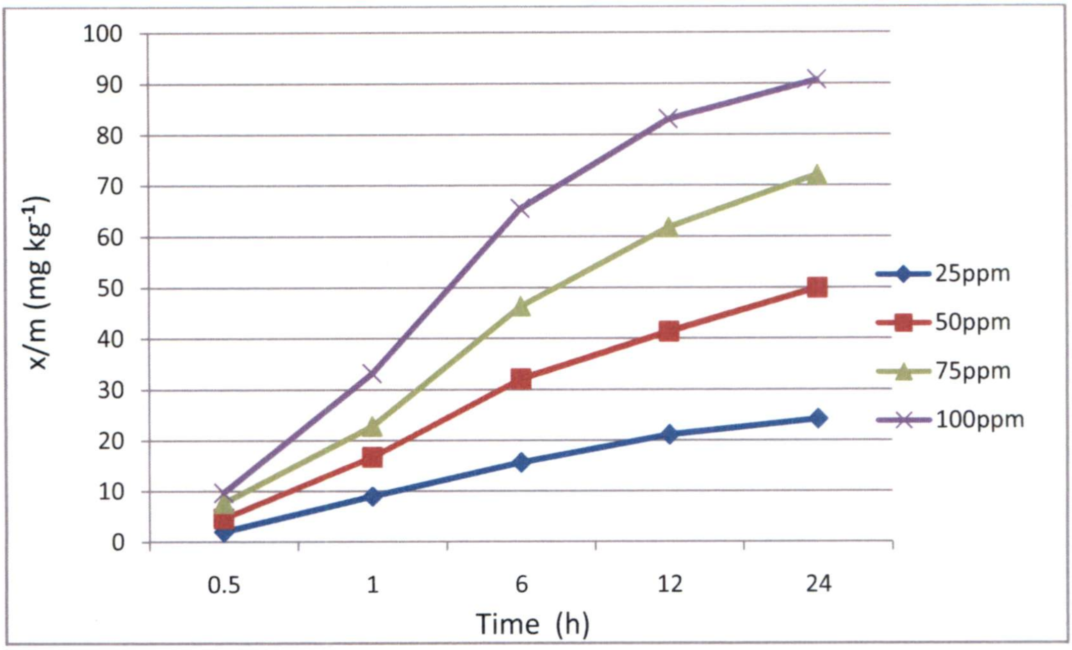


Fig. 7. Sorption of PO_4^{3-} on biochar

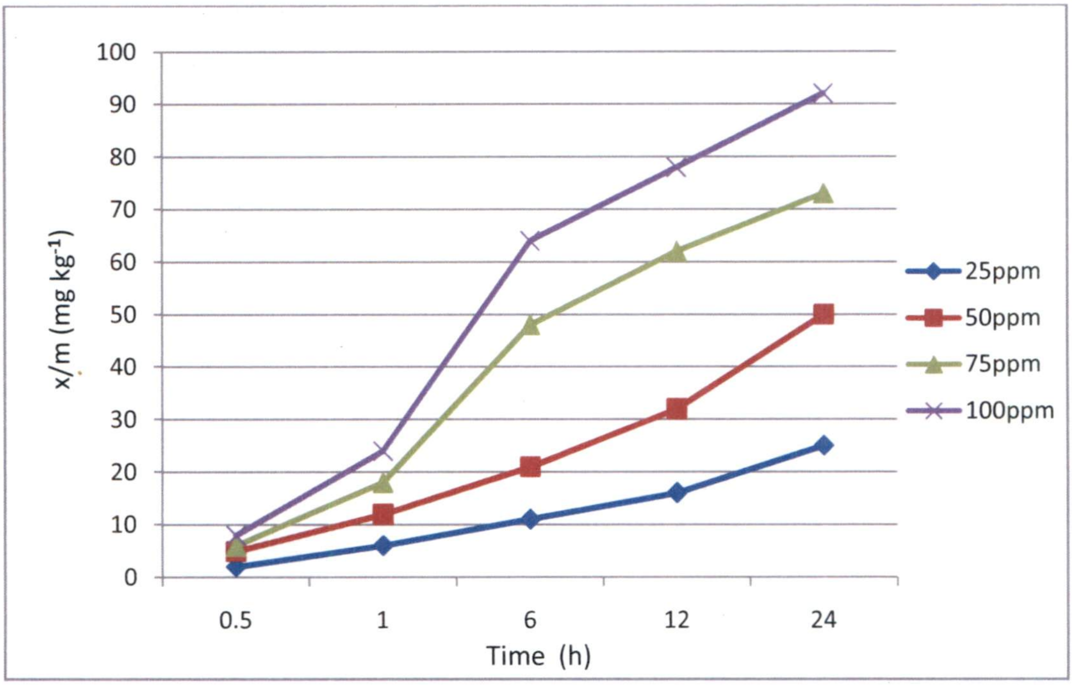


Fig. 8. Sorption of K^+ on biochar

PO_4^{3-} sorption by biochar may be attributed to formation of metal-phosphate precipitate. The formation of $Ca_3\,(PO_4)_2{\cdot}xH2O$ precipitate on biochar suggests that the removal of PO_4^{3-} from aqueous solution is controlled by its precipitation reaction. The reaction can be described as follows:

$$Ca^{2+} + PO_4^{3-} + xH_20 \rightarrow Ca_3\,(PO_4)_2.xH_20$$

With increase in equilibration time and increase in concentration, the K^+ sorption was found to be substantially increased. When 25 mg l^{-1} K^+ solution was equilibrated with biochar, the duration of time required for 100 per cent adsorption was 24 h. We could observe that a longer adsorption period is required for the complete sorption of K^+ even at lower concentrations. But, 97 per cent of K^+ was sorbed when 75 mg l^{-1} was equilibrated for 24 h (Fig. 8). This higher sorption may be due to the concentration gradient existing between the bulk solution and the biochar surface as well as due to the increase in contact time.

In the case of Ca^{2+} also, the same trend was observed. With increase in concentration and equilibration time, there was increase in the sorption of Ca^{2+} (Fig. 9). 23.70 , 48.21, 66.46 and 87.00 mg kg^{-1} Ca^{2+} were found to be sorbed on biochar after 24 h of shaking, when biochar was equilibrated with 25, 50, 75 and 100 mg l^{-1} of the nutrient solutions. Waters *et al.* (2010) observed an increase in Ca sorption with increasing shaking times for the green waste biochar, and the loss was significantly larger than the Ca sorption of the cow manure biochar).

As equilibration time and concentration were increased, the adsorption also was found to be continuously increased in the case of Mg^{2+} (Fig. 10). It can be observed from the data that 100 per cent of Mg^{2+} was found to be adsorbed on biochar surface in 24 h, when 25 mg l^{-1} Mg^{2+} containing solution were provided. The quantity of Mg^{2+} adsorbed was 86 mg l^{-1} after elapsation of 24 h when 100 mg l^{-1} Mg^{2+} was provided.

The experimental results revealed that after 24 h of shaking, 100 per cent Mg^{2+} was found to be sorbed on biochar from nutrient solution containing 25 mg

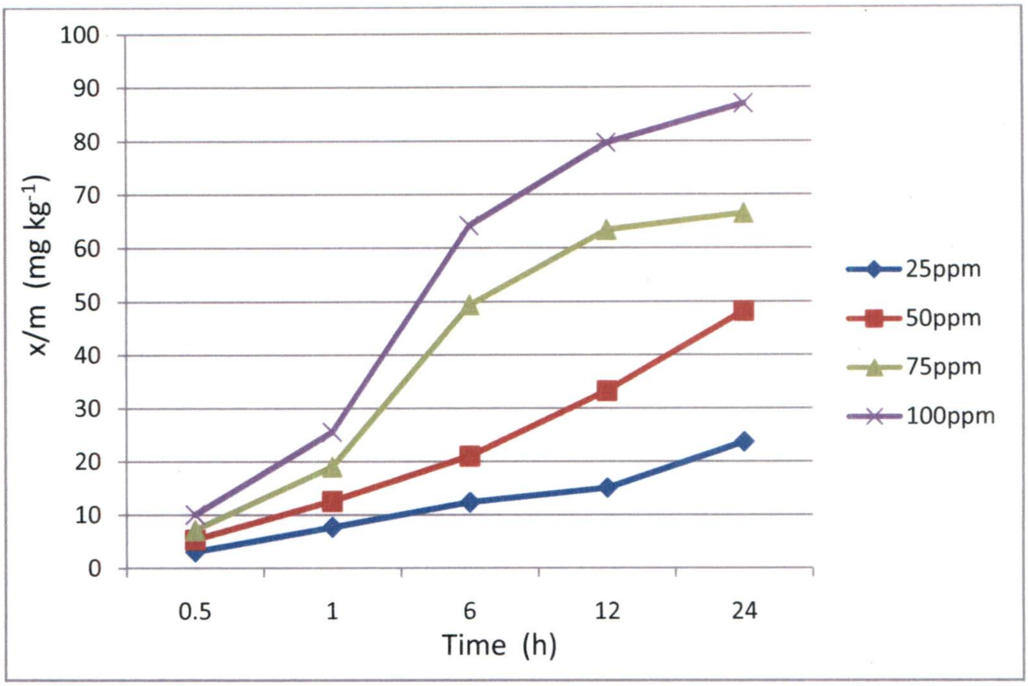


Fig. 9. Sorption of Ca^{2+} on biochar

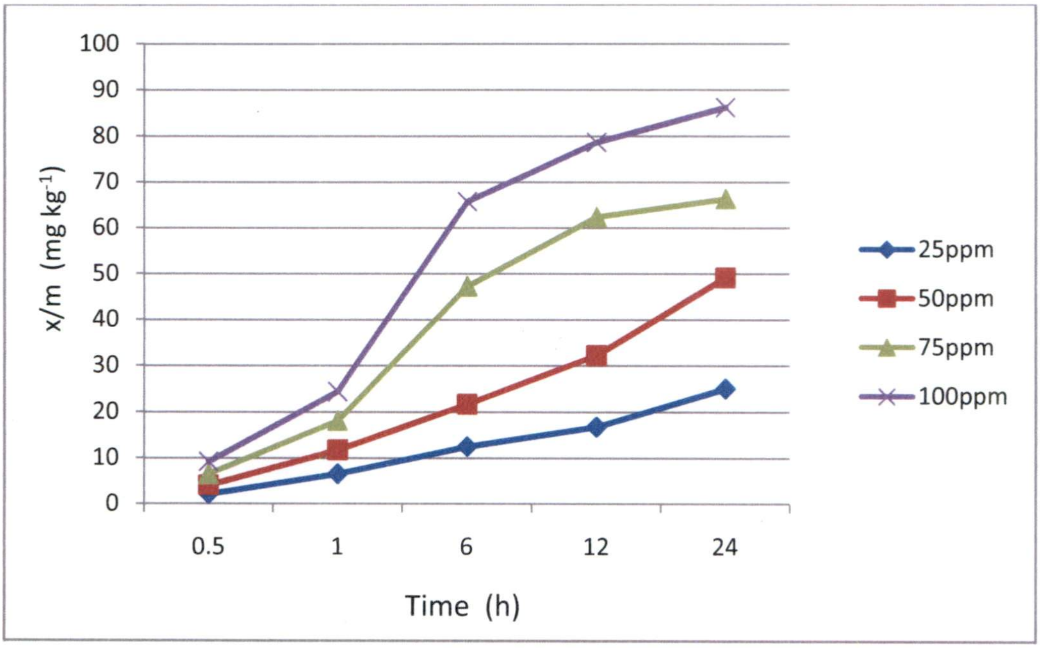


Fig. 10. Sorption of Mg^{2+} on biochar

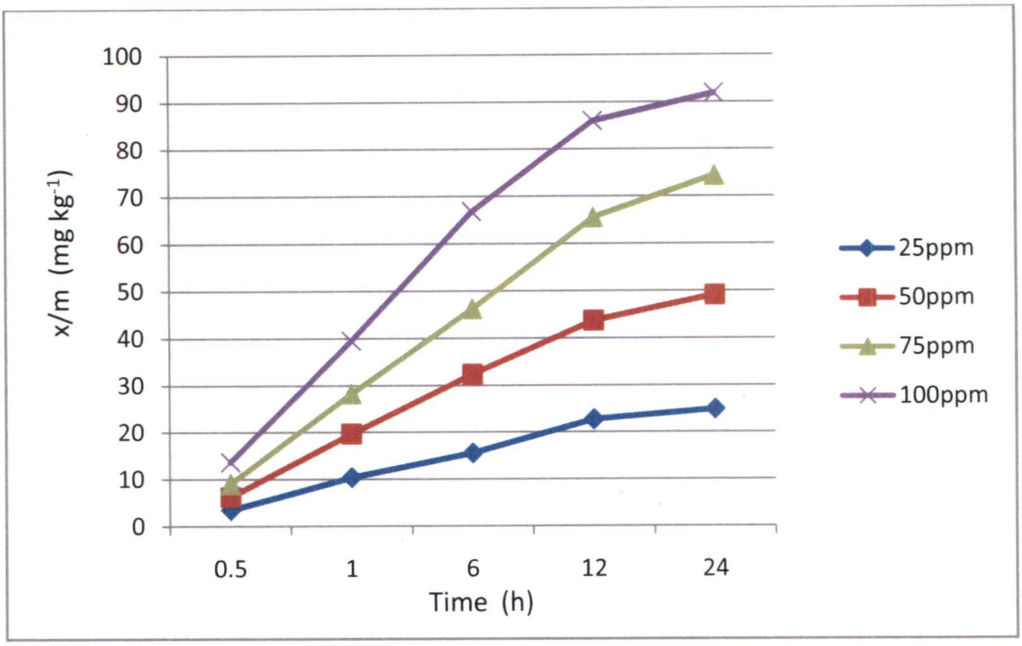


Fig. 11. Sorption of SO_4^{2-} on biochar

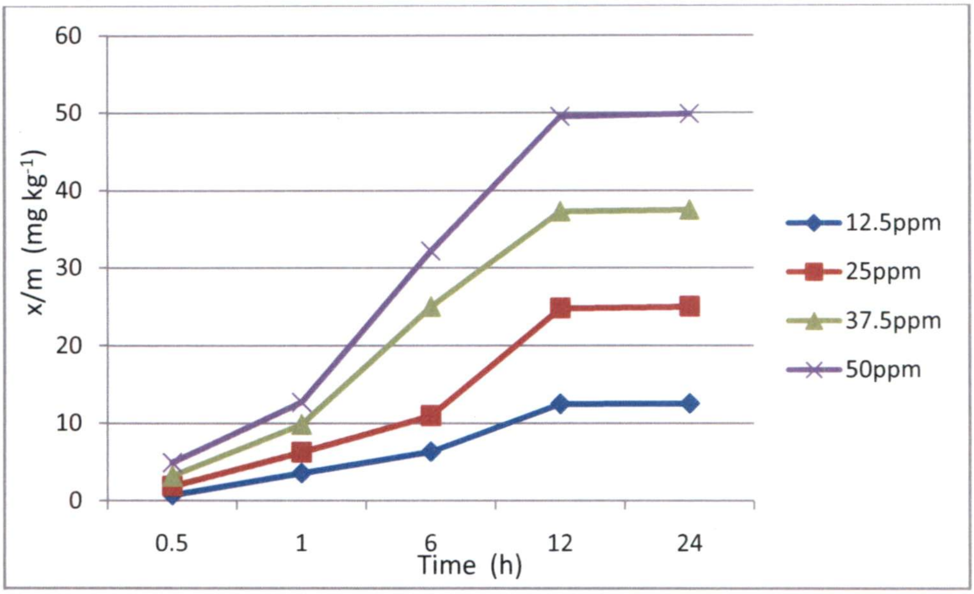


Fig. 12. Sorption of Fe^{2+} on biochar

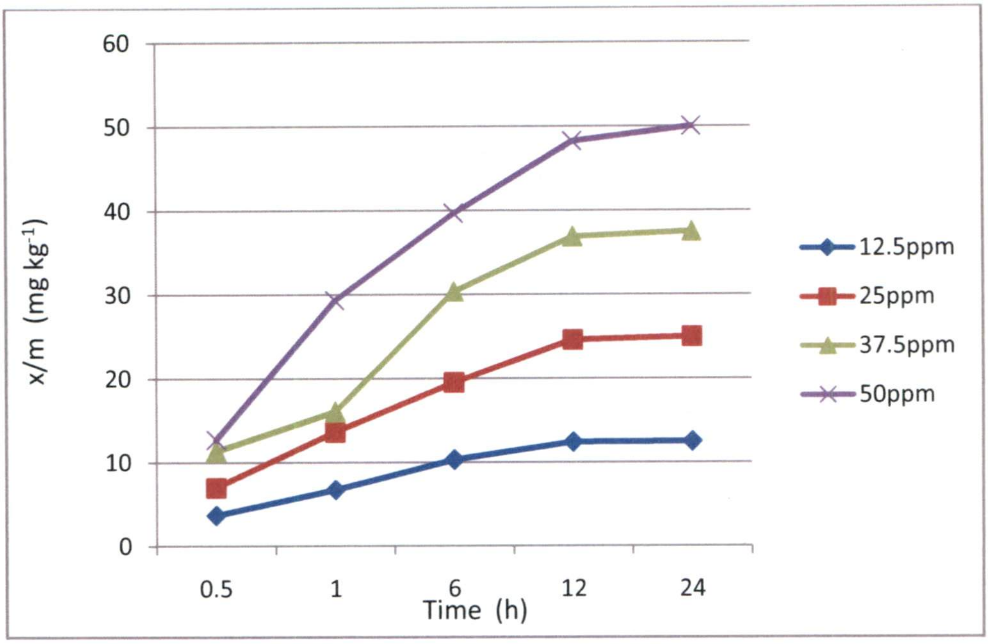


Fig. 13. Sorption of Mn^{2+} on biochar

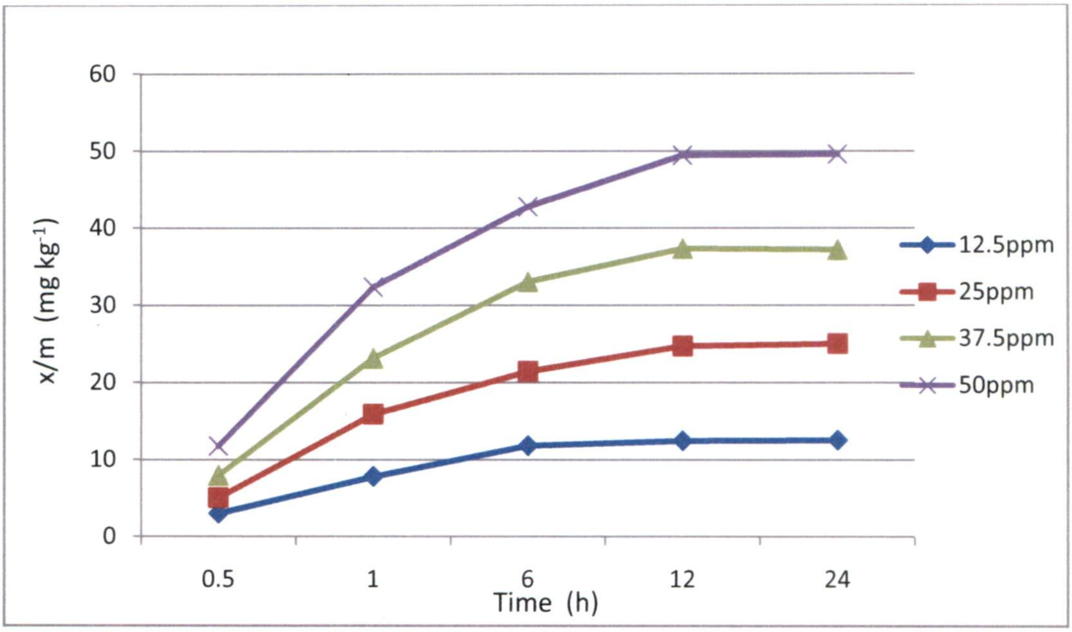


Fig. 14. Sorption of Zn^{2+} on biochar

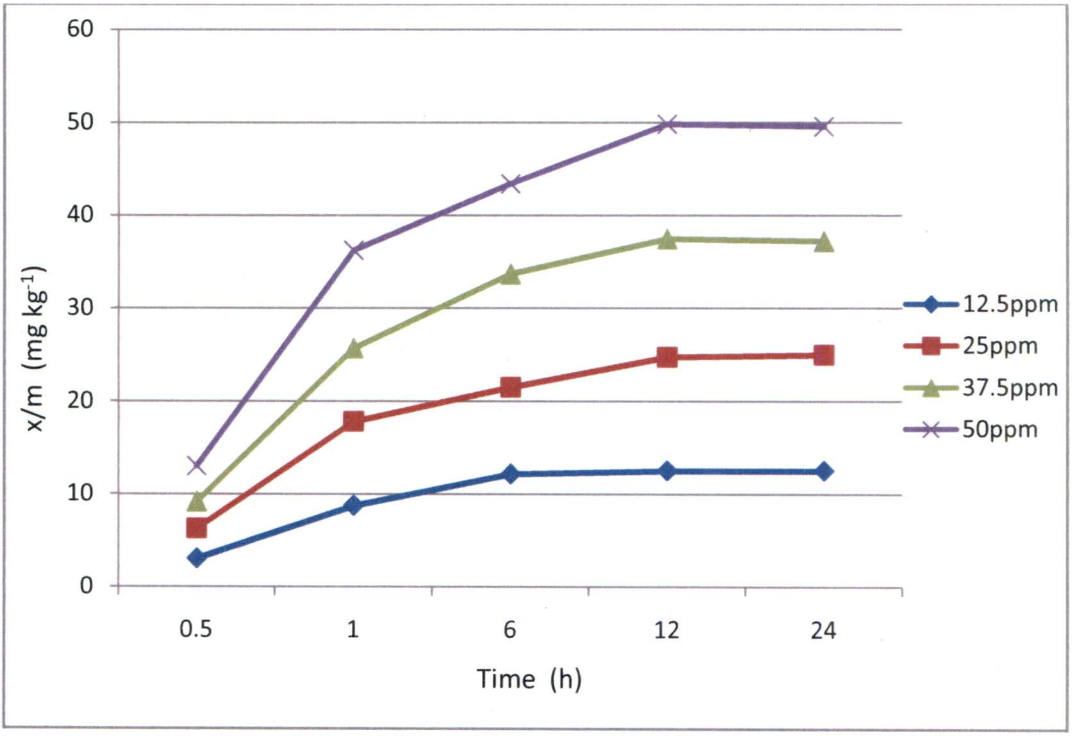


Fig. 15. Sorption of Cu^{2+} on biochar

l^{-1} Mg^{2+}. As the time and concentration of the nutrient solution increased, the quantity of Mg^{2+} sorbed was also found to be increased. The sorption of Mg significantly increased with increasing shaking times for biochar made from cow manure and green waste, and this was significantly larger for the cow manure biochar compared to the green waste biochar (Waters *et al.*, 2010).

With increase in equilibration time and increase in concentration, the adsorption was found to be continuously increased in the case of SO_4^{2-} also (Fig. 11). From the maximum concentration provided (100 mg l^{-1}), 91.84 per cent of SO_4^{2-} was sorbed within one day. It is clear from the data that when 25, 50, 75 and 100 mg l^{-1} SO_4^{2-} were provided, the actual quantity of SO_4^{2-} sorbed on 1 kg biochar was 99.49, 98.15, 99.17 and 91.82 mg kg^{-1} after 24 h of shaking.

The adsorption of Fe^{2+}, Mn^{2+}, Zn^{2+} and Cu^{2+} were found to be increased with increase in concentration and increase in equilibration time. 100 per cent adsorption was observed after 24h. The data is depicted in Fig. 12, Fig.13, Fig.14 and Fig.15.

From the observations, it can be concluded that 100 per cent adsorption of Mn^{2+} was observed for all concentrations after 24 h of shaking. Regarding the sorption of Fe^{2+}, Zn^{2+} and Cu^{2+}, 100 per cent adsorption was observed when biochar was provided with solutions containing concentrations of the nutrient.

Regarding the sorption at 75 mg l^{-1} and 100 mg l^{-1} Zn^{2+} and Cu^{2+}, 99.11 per cent and 99.12 per cent of the given nutrient was adsorbed.

The sorption experiments using biochar revealed that, during the course of time, the per cent of nutrients sorbed on biochar also increased. Quantity of nutrient sorbed on biochar was found to be increased with increase in concentration of the nutrient. In addition to this, anion adsorption was lesser compared to cation adsorption. The high cation adsorption is attributed to the elevated CEC of tender coconut husk biochar (15.26 cmol kg^{-1}) particles and its high SSA (157.93 m^2 g^{-1}) that helps to adsorb a large number of ionic species on its surface. Nutrient retention in soils amended with biochar may be attributed to the sorptive capacity of fresh biochar through charge or covalent interactions (Major *et al.*, 2009).

The comparatively lesser sorption of anions (PO_4^{3-} and SO_4^{2-}) can be related with the higher desorption of these nutrients from biochar when biochar was rinsed with de-ionized water in 1: 100 ratio.

Overall, the laboratory experiments showed that the nutrient (especially of cations) adsorption power of biochar is high. Once biochar is added to an agricultural field as a soil amendment, it may efficiently prevent nutrients from leaching during runoff and make them available to plants through adsorption. Moreover, previous research had revealed that biochar could inhibit the nitrification of ammonium fertilizer (Spokas *et al.*, 2009) and hence it could act as a slow release fertilizer. Therefore, it can be concluded that biochar as a soil amendment can increase crop yield while at the same time increase the use efficiency of applied fertilizers and reduce the use of chemical fertilizers.

5.2.2. Carbon Dioxide Emission Studies Using Biochar and Other Organic Manures

Comparison of the CO_2 emission by biochar and other organic manures showed a significant reduction in CO_2 emission in biochar applied treatments (Fig. 16). The maximum emission was recorded by FYM application @ 2 per cent level (T_4) in soil and the lowest emission was recorded by biochar @ 1 per cent level (T_3).

It can be concluded that biochar application had significant influence on reducing CO_2 emission, compared to other organic amendments like FYM and vermicompost. The highest emission was registered for the treatment T_4 which received FYM @ 2 per cent. There observed a reduction in CO_2 emission by 89.09 per cent at the first fortnight, 88.74 per cent at second fortnight, 88.58 per cent at third fortnight, 88.40 per cent at forth fortnight, 87.87 per cent at fifth fortnight, 86.97 per cent at sixth fortnight, 87.48 per cent at seventh fortnight, 87.35 per cent at eighth fortnight, 84.27 per cent at ninth fortnight, 83.07 per cent at tenth fortnight, 65.73 per cent at eleventh fortnight, 47.47 per cent per cent at twelfth

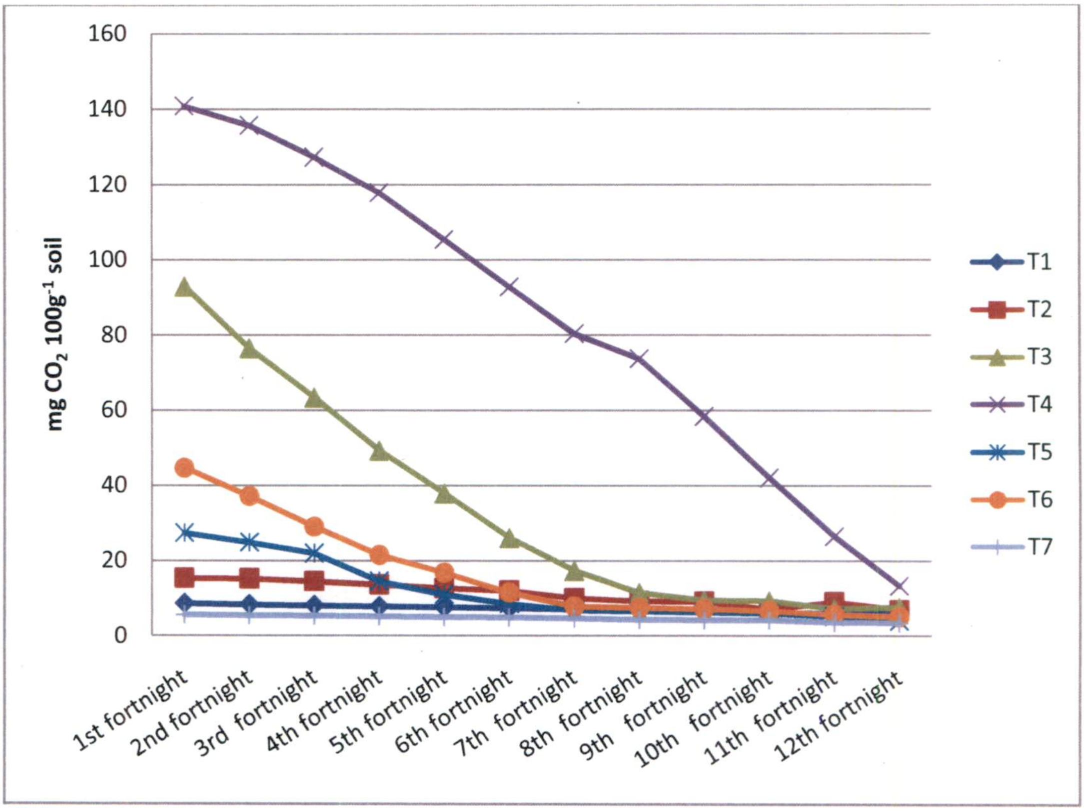


Fig. 16. Effect of treatments on carbon dioxide emission at fortnightly intervals, mg CO_2 100 g^{-1} soil

fortnight and the total emission was found to be reduced by 86.64 per cent and 48.11 per cent when the soil was incubated with biochar @ 2 per cent, compared to the treatments that received FYM @ 2 per cent and vermicompost @ 2 per cent respectively.

Regarding total emission at the end of twelfth fortnight, the highest emission was registered by the treatment which received FYM @ 2 per cent (1014.05 mg CO_2 100 g^{-1}), followed by T_3 which received FYM @ 1 per cent (408.50 mg CO_2 100g^{-1}) and the data is illustrated in Fig. 17. Comparing different levels of biochar used, the lowest emission was registered by treatment that received biochar @ 1 per cent, followed by biochar @ 2 per cent. In treatments receiving biochar, the emission was low compared to other treatments, except control. Comparison of the emission from 2 per cent FYM and 2 per cent BC has revealed that there was about 7.50 times reduction in release of CO_2 in the case of biochar application. As far as emission from biochar was considered, it could be noted that the rate of emission was almost constant throughout the incubating period emphasizing the stability of biochar C in soil.

Islami *et al.* (2011) compared the trends in decomposition dynamics of different amendments and observed that coconut shell biochar recorded the lower rate of decomposition than cattle manure which implies that organic C of biochar with an aromatic structure is more resistant to decomposition.

Instead of adding fresh organic material to soil, conversion of biomass to biochar would be beneficial since biochar is recalcitrant in nature, it can remain in soil for a longer period without decomposition (Gaunt and Lehmann, 2008). In this incubation experiment, there observed a very slow release of CO_2 over an extended period and more C could be sequestered in soil when compared to the other commonly used organic amendments.

Kimetu and Lehmann (2010) measured soil respiration in a field experiment where biochar as well as green manure were applied at 6 t C ha^{-1}. On soil with low organic C contents, biochar resulted in a reduction in C loss as

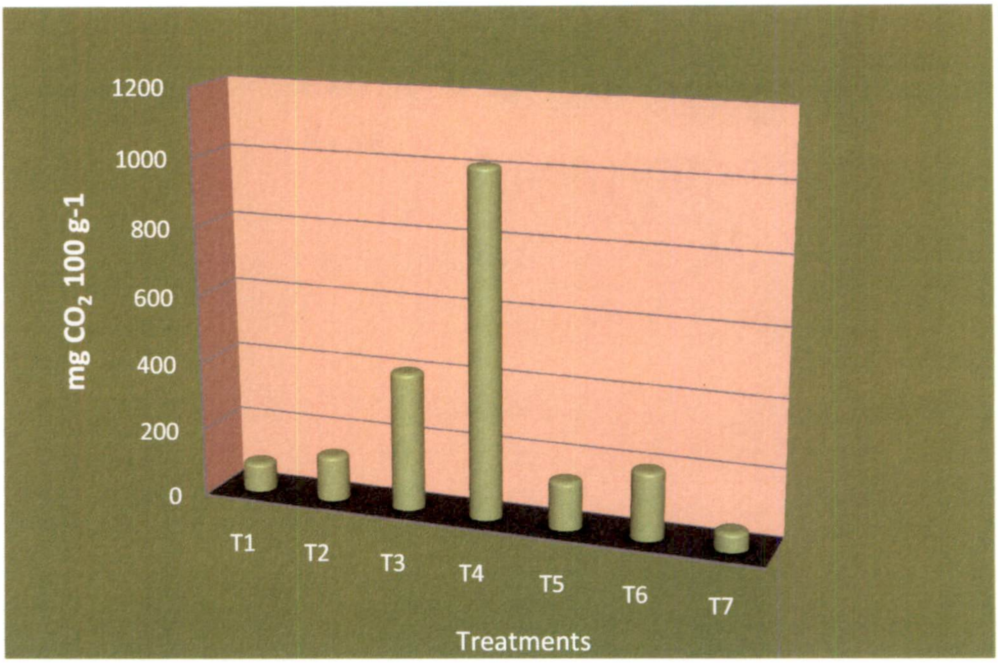


Fig. 17. Effect of treatments on total carbon dioxide emission, mg CO_2 100 g^{-1} soil

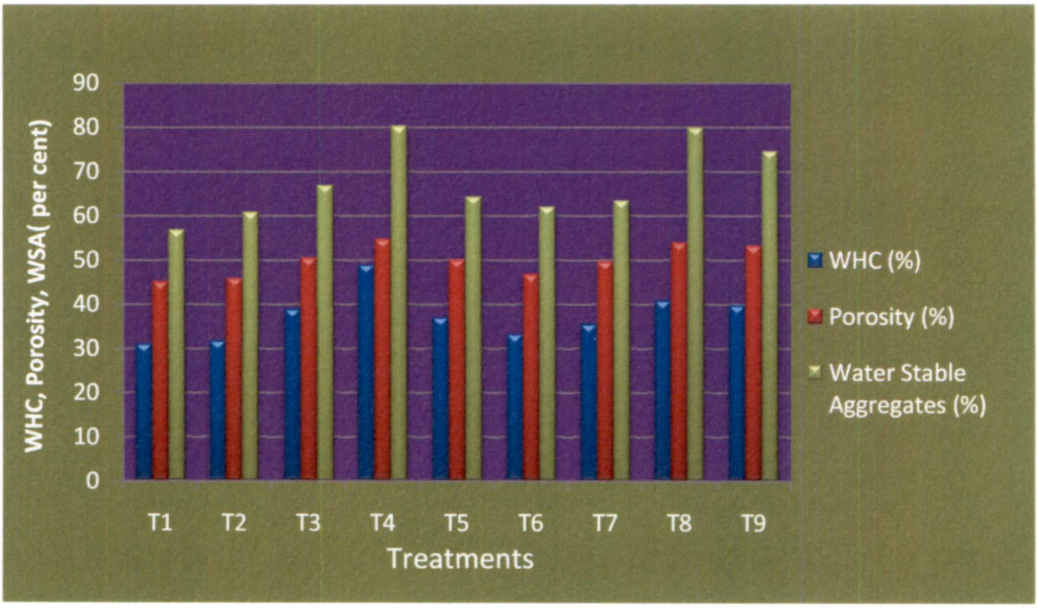


Fig. 18. Effect of treatments on physical properties of soil at fifty per cent flowering stage

respiration by 27 per cent compared to the unamended control, while the green manure resulted in a 22 per cent increase in C loss by respiration. In plots receiving biochar, 6.8 times more C was found in the intra-aggregate fraction (recalcitrant) per unit C respired, when compared to plots where green manure had been applied.

Liu *et al.* (2011) reported that CO_2 emission was reduced by 91 per cent, when a paddy soil was amended with bamboo (*Bambuseae sp.*) and rice straw biochar pyrolyzed at 600°C. Spokas *et al.* (2009) observed >20 per cent reduction in emission of CO_2 from a silt loam soil amended with wood chip biochar compared to un-amended control.

Biochar is generated from waste biomass through the process of pyrolysis (thermo-chemical decomposition of biomass) that can produce energy and sequester carbon. Carbonization of biomass increases carbon aromaticity (Bourke *et al.*, 2007) and recalcitrance relative to its thermally unaltered state, which helps to mitigate the release of CO_2 into the atmosphere through decomposition. The rate of CO_2 uptake of living biomass far exceeds the rate of CO_2 released from biochar when added to soil (Lehmann, 2007), making biochar production an attractive strategy for reducing GHG emissions.

5. 3. FIELD EXPERIMENT

5. 3. 1. Soil Analysis

5. 3. 1. 1. Physical Properties

From the results of the experiment, it can be concluded that all the physical properties were significantly influenced by the application of treatments (Fig. 18).

5. 3. 1. 1. 1. Water Holding Capacity

Different treatments significantly influenced the WHC of soil both at 50 per cent flowering stage and at final harvest stage. WHC increased from 30.89 per cent (POP) to 48.78 per cent by the application of biochar @ 30 t ha^{-1} along with

NPK as per POP and there observed an increase of 57.92 per cent in WHC of the soil at the experimental site. When biochar was applied @ 20 t ha^{-1} along with 2 per cent PGPR and NPK as per POP, the WHC increased by 31.66 per cent. Biochar is predicted to increase the WHC of soil because of increases in particle surface area and storage of water within its porous structure (Lehmann *et al.*, 2003). Biochar has high total porosity, and it can retain water in small pores and thus increase WHC and let the water flow through the larger pores after heavy rains from topsoil to deeper soil layers (Asai *et al.*, 2009). Sokchea and Pretson (2011) and Southavong and Pretson (2011) reported an increase in WHC of soil from 43 to 53 per cent and 40 to 50 per cent, respectively, as a result of biochar application. An experiment carried out by Islami *et al.* (2011) revealed that the available water content was increased from 15.56 to 17.96 per cent by the application of cassava stem biochar @ 15 t ha^{-1}. Glaser *et al.* (2002) have also demonstrated an 18 per cent higher water retention value for Amazonian anthrosol relative to nearby soil with no biochar. Major *et al.* (2009) suggested that due to the physical characteristics of biochar there will be changes in soil pore-size distribution and this could alter percolation patterns, residence time and flow paths of the soil solution. It has also been suggested that if biochar contains sufficient amounts of humic substances that also can increase soil WHC (Piccolo *et al.*, 1996). If WHC of the soil is increased, the availability of water and nutrients will get improved.

5. 3. 1. 1. 2. Porosity

Regarding porosity of the soil, T_4 (biochar @ 30 t ha^{-1}+ NPK) and T_8 (biochar @ 20 t ha^{-1} along with 2 per cent PGPR and NPK) were found to be on par and significantly increased the porosity by 21.22 and 19.66 per cent at fifty per cent flowering stage. At final harvest stage there observed an increase by 18.82 and 16.47 per cent respectively for T_4 and T_8. Biochar application can influence soil porosity and thus soil water retentions via three mechanisms (1) direct pore contribution from pores within the biochar, (2) creation of packing or accommodation pores between biochar and the surrounding soil aggregates, and

(3) through improved persistence of soil pores due to increased aggregate stability. Jones *et al.* (2010) reported that application of 40 t ha^{-1} and 80 t ha^{-1} of green waste biochar to bauxite processing residue coarse sand significantly decreased macroporosity (pore diameters >29 μm) whilst significantly increased mesoporosity (pore diameters between 0.20 and 0.29 μm).

5. 3. 1. 1. 3. Bulk Density

Application of biochar had a beneficial effect on reducing the bulk density of the soil and there observed a decrease by 9.09 and 8.20 per cent respectively at fifty per cent flowering stage and at final harvest stage. The density of biochar is much lower than mineral soil used for the study. Hence, incorporation of biochar can increase the soil volume and reduce the bulk density of the soil. In addition to this, , for the biochar-amended soils, physical dilution effects might have caused reduction in bulk density levels, which agreed with the findings of Busscher *et al.* (2011) who indicated that increasing total organic carbon by the addition of biochar in soils could significantly decrease bulk density by influencing flocculation of soil micro-aggregates. Furthermore, the decrease in bulk density of the biochar-amended soils appears to have also been the result of alteration of soil aggregate sizes, as shown by Tejada and Gonzalez (2007). Githinji (2014) suggested that application of biochar @ 100 per cent (v/v) decreased soil bulk density from 1.33 to 0.36 g cm^{-3} with porosity increasing from 0.500 to 0.773 cm^{3} cm^{-3}. Huanga *et al.* (2013) suggested that the addition of biochar @ 10, 20 and 40 t ha^{-1} to paddy soils led to a decrease in soil bulk density by 9 per cent compared with untreated soils.

5. 3. 1. 1.4. Water Stable Aggregates

Per cent of water stable aggregates was increased significantly by the application of treatments. At 50 per cent flowering stage and final harvest stage, per cent of water stable aggregates was significantly superior for the treatment T_8 that received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP which was on par with T_4 (biochar @ 30 t ha^{-1} + NPK as per POP) and there observed an increase by 40.65 and 41.35 per cent respectively. It can be inferred that the mucilage produced by microbial activity and hyphae in the interface between soil particles and biochar caused soil particles to bind micro-aggregates to form macroaggregates. Biochar, being a rich source of Ca and Mg, helps in supplying these nutrients to the soil, resulting in an increase of Ca and Mg status of soil also helped in improved flocculation of soil aggregates resulting in increase in per cent WSA. The increasing Mean Weight Diameter of the soil aggregates of the biochar-amended soils after 105 days of incubation can be attributed to an increase in the amount of oxidized functional groups after mineralization of the biochar (Cheng *et al.*, 2006),which facilitated flocculation of both the soil particles and the biochar. Six *et al.* (2004) demonstrated that organic amendments can connect soil particles through electrostatic attraction, leading to the formation of micro-aggregates. Liu *et al.* (2012) emphasized that soil aggregate sizes and stability could be significantly increased through the addition of biochar to the soil.

5. 3. 1. 2. pH, EC, CEC, organic C

5. 3. 1. 2. 1. ***pH***

As a key factor in deciding the availability of various nutrients, the changes in soil pH is very important and biochar application showed profound influence on soil pH (Fig. 19). The initial pH of the soil at the experimental site was determined to be 4.80. By the application of biochar @ 30 t ha^{-1} + NPK there was significant increase in pH to 6.50 at 50 per cent flowering stage and it was on par with the pH obtained when biochar was applied @ 20 t ha^{-1} along with PGPR and NPK (6.36) . There was an enhancement in soil pH by 1.70 units by the application of tender coconut husk biochar. This study supports reports of several other studies where biochar application increased the pH of acidic soils (Lehmann *et al.*, 2003). Increased concentration of alkaline metal (Ca^{2+}, Mg^{2+}, and K^{+}) oxides present in biochar, and a reduced concentration of soluble soil Al^{3+} could explain such effects (Steiner *et al.*, 2007). Biochar is typically an alkaline material and has

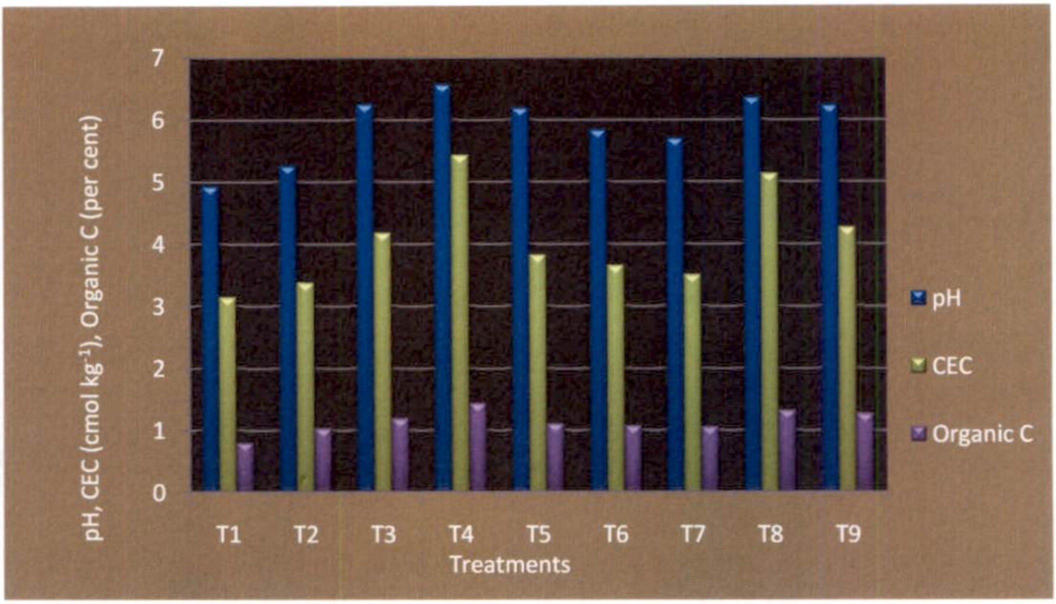


Fig. 19. Effect of treatments on pH, CEC and Organic C status of soil at fifty per cent flowering stage

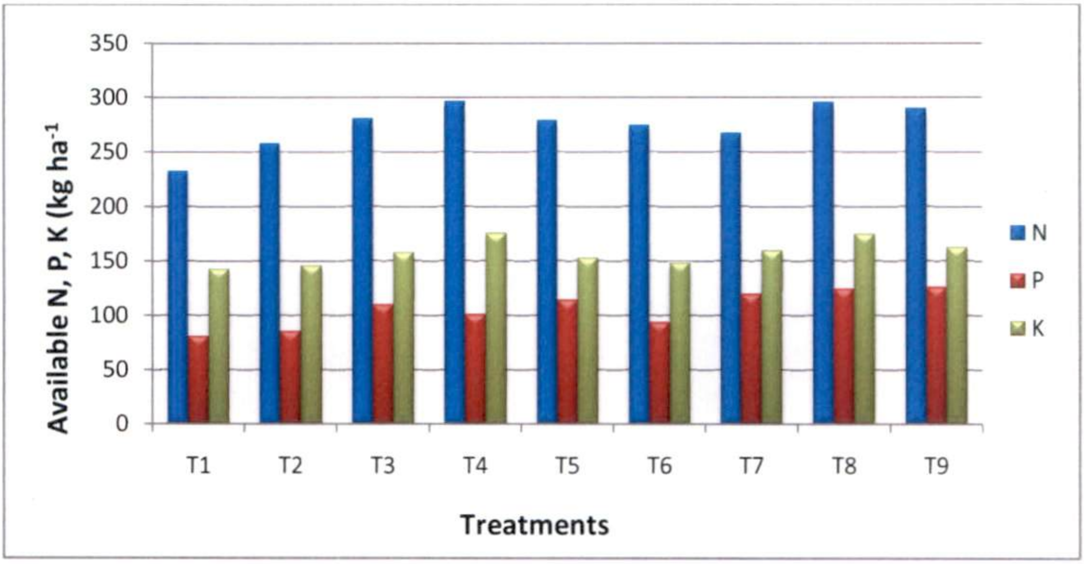


Fig. 20. Effect of treatments on available N, P, K status of soil at fifty per cent flowering stage

been shown to increase the pH of acidic soils to levels optimal for crop growth (pH of 6-7).The high liming potential of the biochar (pH > 9.0) raised the pH of the highly weathered soil. The results further show that pH increased significantly with increasing application rates of biochar, reflecting the fact that the liming potential increased with increasing application rates of biochar. This correlated with the results of Yuan *et al.* (2011), who indicated a significantly positive linear correlation between biochar-treated soil pH and the rate of biochar applied. The results are in conformity with the results obtained by Southavong *et al.* (2012) who investigated the effect of biochar and biodigester effluent on biomass yield of water spinach and on soil fertility and concluded that application of biochar @ 40 t ha^{-1} increased the soil pH from 4.68 to 6.22. Jien and Wang (2013) applied biochar @ 2.50 per cent, and 5.00 per cent to an acidic Ultisol and observed a significant improvement in soil pH from 3.90 to 5.10. Van Zwieten *et al.* (2010a) reported that biochar from paper mill waste @ 10 t ha^{-1} in a Ferrosol significantly increased pH from 4.20 to 5.93.

Depending on the biochar biomass used, basic cations such as Ca^{2+}, K^{+}, Mg^{2+}, and silicon (Si) can form alkaline oxides or carbonates during the pyrolysis process. Following the release of these oxides into the environment, they can react with H^{+} and monomeric Al^{3+} species, raise the soil pH, and decrease exchangeable acidity (Novak *et al.*, 2009). Furthermore, research conducted by him on pecan shell derived biochar revealed that there was a high concentration of calcium oxide in the biochar, which neutralizes soil acidity as follows:

$$2Al - soil + 3CaO + 3H_2O \rightarrow 3Ca - soil + 2Al\,(OH)_3$$

The reaction describes the reduction in exchangeable acidity whereby Ca replaces the monomeric Al species on the soil exchangeable sites and generates alkalinity. Subsequently, there is an increase in soil solution pH as a result of the reduction of the readily hydrolysable monomeric Al and the subsequent formation of the neutral [Al $(OH)_3$] species (Sparks, 2003).

When biochar has high concentrations of carbonates, it may have effective liming properties for overcoming soil acidity (Chan and Xu, 2009).

5. 3. 1. 2. 2. Electrical Conductivity

The initial soil had an EC of 0.42 dS m^{-1}. At 50 per cent flowering stage, by the application of biochar, EC was significantly increased to 0.87 dS m^{-1}. This is in conformity with the results obtained by Chintalaa *et al.* (2014) who concluded that corn stover biochar significantly increased EC of acidic soil by 21, 40, and 83 per cent as application rate increased from 52, 104, and 156 Mg ha^{-1}, respectively, whereas the switch grass biochar had increased the EC of soil by 19, 51, and 57 per cent respectively.

5. 3. 1. 2.3. Cation Exchange Capacity

By the application of treatments, there observed a significant improvement in soil CEC at 50 per cent flowering stage (Fig. 19). The initial soil had CEC of 2.56 cmol kg^{-1}. At 50 per cent flowering stage, T_4 (biochar @ 30 t ha^{-1} + NPK as per POP) registered the significantly superior value of 5.43 cmol kg^{-1}, which was on par with T_8 (5.13 cmol kg^{-1}) that received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP. The improvement of the CEC by 72.93 per cent (T_4) and 63.38 per cent (T_8) can be attributed to the high SSA of biochar, which resulted from its porous structure. Additionally, slow oxidation of the biochar increased the number of carboxylic and phenolic functional groups, which in turn increased the CEC of the amended soil. The results of the present study are in agreement with the findings of Jien and Wang (2013) who applied biochar @ 2.50 per cent, and 5 per cent to an acidic Ultisol observed an improvement in soil CEC from 7.41 to 10.80 cmol (+) kg^{-1} significant increases in soil pH from 3.90 to 5.10. In a greenhouse study, Van Zwieten *et al.* (2010a) found that biochar increased the CEC of a Ferralsol soil from 4.00 cmol to 10.50 cmol (+) kg^{-1}.

The normal CEC ranges in soils would be from < 3 cmol kg^{-1} for sandy soils low in organic matter to > 25 cmol kg^{-1} for soils high in certain types of clay or organic matter. Hence, low-temperature biochar which contained more oxygen-containing functional groups and a higher CEC, can enhance the adsorption ability to retain cationic nutrients.

All the physical properties of the soil *viz.* WHC, porosity, bulk density and WSA were significantly improved by the highest rate of application of biochar 30 t ha^{-1} along with NPK and it was on par with biochar @ 20 t ha^{-1} along with 2 per cent PGPR and NPK as per POP.

5. 3. 1. 2. 4. Organic Carbon

The initial organic carbon content of the soil was 0.76 per cent and there observed an improvement in soil organic C by 81.01 per cent as a result of biochar application, compared to POP (control). The data is illustrated in Fig. 19. Significantly superior value of 1.43 per cent was shown by T_4 (biochar @ 30 t ha^{-1} + NPK as per POP) which was on par with T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP (1.32 per cent) and T_9 (1.27 per cent). The least value was registered by the treatment without biochar. The tender coconut husk biochar used for this study had high C content of 72.30 per cent. This might be the reason for increase in SOC after biochar application. This is in conformity with the results obtained by Huanga *et al.* (2013) who observed that addition of biochar up to 40 t ha^{-1} to paddy soils led to increase in SOC by 33 per cent compared with untreated soils and that of Sukartono *et al.* (2011) where application of coconut shell biochar @ 15 Mg ha^{-1} increased the soil SOC from 0.89 to 1.33 mg kg^{-1}. Van Zwieten *et al.* (2010a) reported that biochar @ 10 t ha^{-1} in a Ferrosol significantly elevated total soil C by 0.50 per cent. Islami *et al.* (2011) also arrived at the conclusion that application of cassava stem biochar @ 15 t ha^{-1} increased the total organic C from 9.50 to 25.20 g kg^{-1}.

It is obvious that the treatments had significant influence on organic C status of soil at final harvest stage also. There was no significant reduction in SOC at final harvest stage, compared to that at fifty per cent flowering stage. This might be due to the fact that biochar is much more persistent in soil than any other form of organic matter that makes it a prime candidate for carbon sequestration.

Because of its aromatic structure dominated by aromatic C, biochar has been found to be biochemically recalcitrant compared to uncharred, parent organic matter and have considerable potential to enhance the long term soil carbon pool.

5.3.1.2. 5. The Effect of Biochar on Availability of Nutrients in Soil

Biochar application had profound effect on availability of all the nutrients in soil. This occurs as a function of biochar's high porosity and surface to volume ratio, together with an increase in the pH of acid soils, attributed to the basic compounds found in biochar (Chan *et al.*, 2007). Liang *et al.* (2006) reported that both an increase in surface area and CEC are the possible reasons for the long term effects that biochar has on nutrient availability.

The immediate beneficial effects of biochar additions for nutrient availability are largely due to higher K, P, and Zn availability, and to a lesser extent, Ca and Cu (Lehmann *et al.*, 2003). Longer-term benefits for nutrient availability include a greater stabilization of organic matter, concurrent slower nutrient release from added organic matter, and better retention of all cations due to greater CEC.

5. 3. 1. 2. 5.1. Available Nitrogen

Being the most important nutrient in plant nutrition, the data on available N need a thorough study and interpretation. A perusal of the data revealed that by the application of treatments, there was increase in the availability of N in soil at 50 per cent flowering stage, followed by a decrease due to uptake of N by the plant at final harvest stage. There was significant difference between the treatments in availability of N due to application of treatments (Fig. 20). The availability of N was significantly superior for T_4 that received the highest rate of biochar i.e, @ 30 t ha^{-1} + NPK as per POP (296.75 kg ha^{-1}) and it was on par with T_8 (295.45 kg ha^{-1}). Widowatil and Asnah (2014) conducted a field experiment to study the effect of biochar @ 30 t ha^{-1} prepared from organic waste and reported an increase in the available N in soil by 39 to 53 per cent. Rondon *et al.* (2007) concluded that biochar @ 90 g kg^{-1} soil increased the proportion of fixed N from 50 to 72 per cent. Islami *et al.* (2011) also concluded that application of cassava stem biochar @ 15 Mg ha^{-1} increased the available N in soil from 0.80 to 1.20 g kg^{-1}.

The increased availability of N is attributed to the nutrient addition from biochar and reduction in leaching losses. CEC and surface area of the added biochar resulted in reduced leaching losses of N fertilizer and improved the adsorption of NH_4^{+}. High biochar application levels between 10 and 20 per cent by weight have been shown to reduce NH_4^+ leaching in Ferralsol and Anthrosol soils (Lehmann *et al.*, 2003). Sika (2012) concluded that biochar application @ 0.50, 2.50, and 10.0 per cent significantly reduced the leaching of NH_4^+ by 12, 50 and 86 per cent respectively.

Plant based biochar consists of various N containing structures which include amino acids, amines, and amino sugars. When subjected to pyrolysis, these structures get condensed and form heterocyclic N aromatic structures (Cao and Harris, 2010), which may possibly not be available for plant use (Gaskin *et al.*, 2010). Consequently, the residual N in the biochar is largely found as recalcitrant heterocyclic N rather than bio-available amine N (Cao and Harris, 2010; Novak *et al.*, 2009). Hence, to counter the potentially unavailable biochar N, it has been found that there is a positive effect when biochar was applied together with the addition of N fertilizer (Steiner *et al.*, 2008), thus showing that biochar has the potential to improve the efficiency of mineral N fertilizer. In addition, biochar is suggested as being economically viable due the reduction in the amount spent on commercial mineral fertilizers (Steiner *et al.*, 2008).

Applications of biochar (Gundale and DeLuca, 2006) can increase nitrification. The biochar micro-environment may also provide a favourable niche (fine structural pores) in which oxygen concentration declines; for nitrogenase to function effectively, low oxygen tensions are required with Fe and Mo ions (Thies and Rillig, 2009).

The availability and rate of mineralization of organic N found in biochar applied soil provides an indication of the biochar's ability of being a slow release N fertilizer (Chan and Xu, 2009).

The results further confirm that, biochar as soil amendment can efficiently utilize the nutrients by holding ammonium ions in soils and inhibiting nitrification.

5. 3. 1. 2. 5.2. Available Phosphorus

By the application of treatments, at fifty per cent flowering stage, there was an increase in available P status when compared to initial value (75.15 kg ha^{-1}) because P of addition (Fig. 20) even though there was no significant difference between the treatments . Among the treatments applied, T_9 which received biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP recorded the highest value and there observed 55.95 per cent increase in available P status by the application of biochar. At final harvest stage, available P status in the soil improved by 58.11 per cent, compared to the initial value. The basis for increased P availability is attributable to the fact that biochar inherently contains a high content of soluble P salts formed during pyrolysis (DeLuca *et al.*, 2009). Effect of AMF and increased surface area helped for increasing P availability. Ogawa and Yamabe (1986) had used biochar as a carrier substrate for both *Rhizobia* and for AMF over the past 20 years with excellent success.

The results of the present study are in conformity with that obtained by Sukartono *et al.* (2011) where application of coconut shell biochar @ 15 t ha^{-1} increased the soil organic C from 14.44 to 22.39 mg kg^{-1}. Widowatil and Asnah (2014) conducted a field experiment to study the effect of biochar @ 30 t ha^{-1} prepared from organic waste and reported an increase in the available P in soil by 179 to 208 per cent.

The availability of P is very important since it directly reflect the immediate P nutrition to plants. Soils found in tropical regions are particularly poor in plant available P resulting in P deficient environments. These soils contain sesquioxides that have the ability to strongly sorb phosphate (Turner *et al.*, 2006), and thereby creating a sink on the availability of inorganic P for plants (Oberson *et* *al.*, 2006). By the application of biochar, soil P status can be improved significantly.

5. 3. 1. 2. 5. 3. Available Potassium

The details relating to the changes in available K due to the effect of various treatments are presented in Fig. 20. Among the treatments, T_4 and T_8 were found to be on par and there observed an increase by 22.96 and 40.07 per cent respectively at fifty per cent flowering stage and at final harvest stage of the crop as a result of biochar application. The relatively high K content in biochar and its ability to sorb considerable amount of K^+ from soil solution results in reducing the leaching losses of K and thus contribute to the increased availability of K in soil. A slight decline in the value of available K at final harvest stage than that observed at fifty per cent flowering stage corresponds to the nutrient uptake by the crop.

Widowatil and Asnah (2014) conducted a field experiment to study the effect of biochar @ 30 t ha^{-1} prepared from organic waste and reported that biochar application increased the availability of K by 69 to 89 per cent in maize. The sole application of biochar increased maize production (6.24 t ha^{-1}) by 14 per cent compared sole application of KCl fertilizer (5.45 t ha^{-1}) and dual application of biochar and 75 per cent lower dosage of KCl fertilizer application increased maize production by 29 per cent. Application of biochar and KCl fertilizer at the rate of 50 kg ha^{-1} resulted in the highest relative K fertilizer efficiency (18 per cent).

5. 3. 1. 2. 5.3. Exchangeable Calcium

It had been statistically observed that application of treatments had significant influence on available Ca in soil at fifty per cent flowering stage and at final harvest stage. At fifty per cent flowering stage, T_4 (3.00 cmol kg^{-1}) was on par with T_8 (2.50 cmol kg^{-1}) and T_9 (2.50 cmol kg^{-1}). At final harvest stage also, the same trend was observed and there was slight decrease in available Ca in soil at final harvest stage than that at fifty per cent flowering stage. The improvement in Ca status is attributed to the relatively high Ca content in the biochar made from tender coconut husk and also due to the fact that biochar can sorb considerable amount of Ca^{2+} on its surface because of its high CEC and this resulted in reduced leaching of this nutrient.

Major *et al.* (2010a) concluded that application of 20 t ha^{-1} of biochar improved the availability of Ca by 77 to 320 per cent in maize. Van Zwieten *et al.* (2010a) assessed the effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility in a glasshouse study and reported that biochar @ 10 t ha^{-1} in a ferrosol significantly increased exchangeable Ca levels from 1.23 to 8.87 cmol (+) kg^{-1}. Widowatil and Asnah (2014) found out that application of biochar @ 30 t ha^{-1} increased the availability Ca^{2+} by 61 to 70 per cent

5. 3. 1. 2. 5.5. Exchangeable Magnesium

The dynamics of Mg closely follows the trend of Ca with increased concentration at fifty per cent flowering than at final harvest stage. As in the case of Ca, here also T_4 (biochar @ 30 t ha^{-1} + NPK as per POP) and T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP recorded the superior value of 1.25 cmol kg^{-1} and this data was found to be on par with T_9 (1.00 cmol kg^{-1}) which received biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP. There observed an increase by 200 per cent, compared to the initial value. Major *et al*, 2010a also found that the available Mg content increased from 64 per cent to 217 per cent when wood biochar was applied @ 20 t ha^{-1} in maize. Sukartono *et al.* (2011) also reported that application of coconut shell biochar increased the soil Mg status from 1.32 to 1.54 cmol kg^{-1}.

5. 3. 1. 2. 5.6. Available Sulphur

Available S status of the soil was found to be increased by the application of different treatments. The initial S status of the soil before the experiment was 17.69 kg ha^{-1} which increased to the tune of 83.91 per cent at fifty per cent flowering stage and 106 per cent at final harvest stage for the treatment , T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP, compared to POP. The observed increase in available S status is due to the addition from biochar, P fertilizer and by the action of PGPR.

5. 3. 1. 2. 5.7. Available Iron, Manganese, Zinc and Copper

The data analysis shows that the available Fe, Mn, Zn and Cu status of the soil had significantly improved by the application of treatments both at fifty per cent flowering stage and at final harvest stage. This is due to the fact that biochar from tender coconut husk is a rich source of micronutrients. Fe and Mn are associated with many organic compounds in biomass, and largely retained during biochar formation (Amonette and Joseph, 2009). In the pecan shell based biochar investigation carried out by Novak *et al.* (2009), the soil had increased Mn concentrations after 67 day trial period because of the fact that Mn was largely retained during biochar formation due to its high association with a number of organic and inorganic forms in the biomass.

5. 3. 2. Effect of Treatments on Carbon Dioxide Emission and Carbon Sequestration in Field

From the experimental results, it is evident that application of biochar significantly reduced CO_2 emission from soil, compared to other organic manures. (Fig. 21)

In all the treatments, the emission was highest during the first two weeks after planting. After that, there observed a decreasing trend during the crop growing period. This decrease was more gradual in those treatments which received biochar. Thus, emission of CO_2 was more or less constant in all the biochar treatments.

Considering the total emission, the lowest emission was registered by the treatment T_2 that received biochar @ 10 t ha^{-1} and there observed 94.11 per cent reduction, followed by T_5 (90.06 per cent) which received biochar @ 20 t ha^{-1}

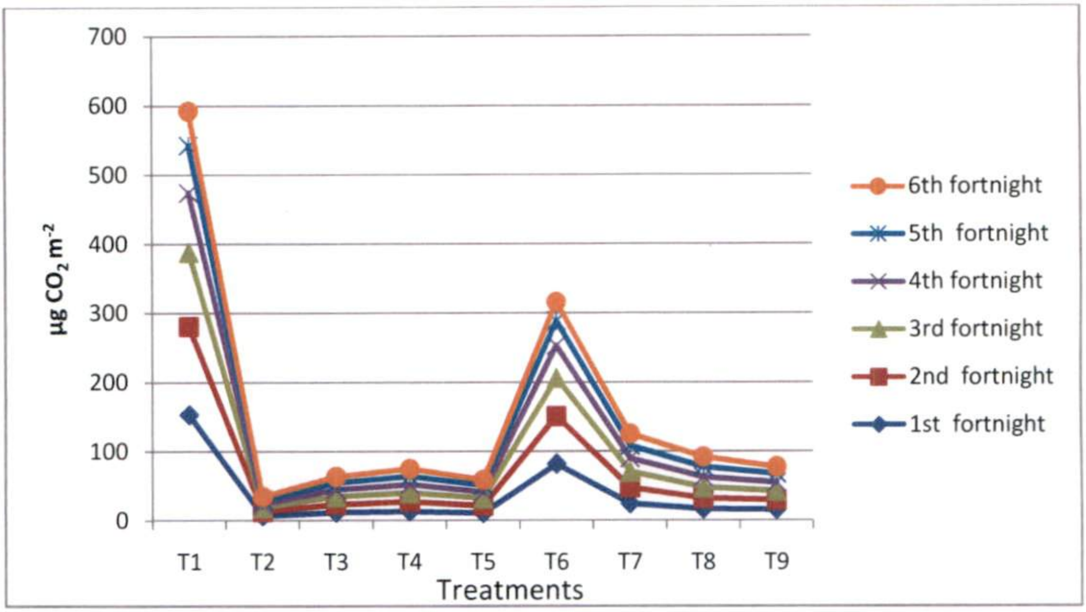


Fig. 21. Effect of treatments on carbon dioxide emission in field

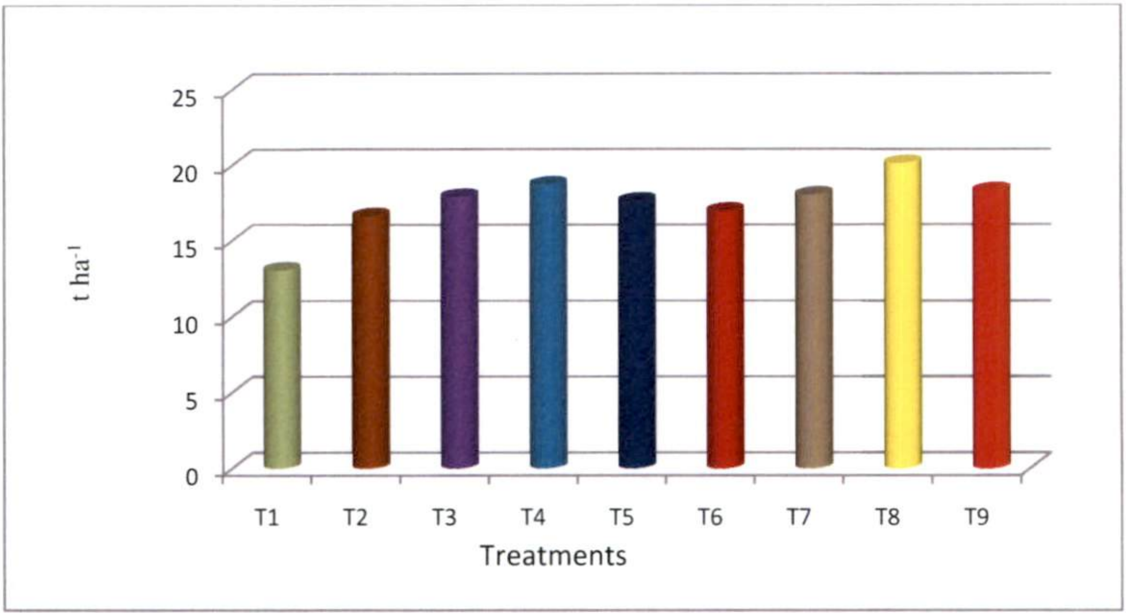


Fig. 22. Effect of treatments on yield of yard long bean

along with 75 per cent NPK, compared to POP. The highest emission was recorded by POP, followed by T_6 which received biochar @ 10 t ha^{-1} + FYM @ 10 t ha^{-1}+ 75 per cent NPK as per POP. Regarding total emission while applying the treatments T_4 and T_8, there observed a reduction by 87.36 and 84.46 per cent respectively, assuming T_1 as control.

The total emission follows the order: $T_2 < T_5 < T_3 < T_4 < T_9 < T_8 < T_7 < T_6 < T_1$. Comparing the emission from T_2, T_6 and T_7, the rate of emission was highest for the treatment T_6 which received FYM @ 10 t ha^{-1}, followed by T_7 which received vermicompost @ 5 t ha^{-1} and the least emission was registered by the treatment that received biochar @ 10 t ha^{-1} as the organic amendment. Hence, compared to other oragnic manures, application of biochar can reduce CO_2 emission significantly.

After the cropping period, treatment T_1 evolved maximum amount of CO_2 (5574.20 mg ha^{-1}) and the least emission was registerd by T_2 (34.87 mg ha^{-1}) that emphasizes the fact that if we are applying biochar @ 10 t ha^{-1} along with NPK instead of POP, 5888.03 mg of CO_2-C can be sequestered from 1 ha land. The best treatment wirh respect to yield (T_8) could sequester 328.11 mg of CO_2-C, compared to POP.

Instead of adding fresh organic material to soil, conversion of biomass to biochar would be beneficial since biochar is recalcitrant in nature, it can remain in soil for a longer period without decomposition (Gaunt and Lehmann, 2008). Kimetu and Lehmann (2010) measured soil respiration in a field experiment where biochar as well as green manure were applied @ 6 t C ha^{-1}. On soil with low organic C contents, biochar resulted in a reduction in C loss by respiration by 27 per cent compared to the unamended control, while the green manure resulted in a 22 per cent increase in C loss by respiration. In plots receiving biochar, 6.80 times more C was found in the intra-aggregate fraction per unit C respired, when compared to plots where green manure had been applied.

5. 3. 3. Effect of Different Treatments on Biometric Characters of Yard Long Bean

In the present study, application of biochar @ 20 t ha^{-1} along with 2 per cent PGPR and NPK as per POP resulted in earliest flowering. Biochar application @ 30 t ha^{-1} also performed in the similar way. This is due to the fact that biochar application caused an increase in plant growth by the supply of nutrients contained in it as well as increasing nutrient use efficiency of applied nutrients resulting in better metabolic partitioning. This helps the plant in reaching the reproductive stage earlier. A prolonged reproductive period was also noticed for the same treatment in which biochar was applied @ 20 t ha^{-1} along with 2 per cent PGPR and NPK as per POP. Treatment that received POP (T_1) took comparatively more days for first flowering and fifty percent flowering and shorter reproductive period.

The significantly superior vine length (517.50 cm) and number of leaves (240) per plant were registered by the treatment that received biochar @ 20 t ha^{-1} along with 2 per cent PGPR and NPK as per POP and it was followed by T_4. Biometric characters were greatly influenced by the progressive additions of biocahr @10 t ha^{-1} to 30 t ha^{-1}, when it was applied with NPK as per POP. The results are in conformity with that obtained by Southavong *et al.* (2012) who reported that application of rice husk biochar to soil @ 40 t ha^{-1} increased plant height, number of leaves per plant, leaf width and foliage yield of water spinach (18.10 t ha^{-1}).

From the experimental results, it can be realized that biochar application had significant influence on nodule formation in yard long bean. Among the treatments, T_8 (biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP) recorded significantly superior value of 18 nodules per plant and it was on par with T_4 (biochar @ 30 t ha^{-1} + NPK as per POP) which recorded 17 nodules per plant. An increase of 350 per cent and 325 per cent respectively for T_8 and T_4 over POP were noticed. The increased nodulation can be related with the fact that

Rhizobia shows increased function in neutral pH soils, so increasing alkalinity in acidic soil enhances nodulation and fixation. Biochar and PGPR had contributed significantly for the multiplication of Rhizobium. The rhizobial population was able to derive large amount of metabolic fuel from the actively growing plants that resulted in better nodulation. The root exhudates helped in the buildup of beneficial microbial population by biochar into the rhizosphere of the plant. Thus the micro-environment created by the interaction between chemicals secreted by living roots and microorganisms in the rhizosphere positively influenced root growth and thereby nodulation. Biochar application alone has also got effect on increasing nodulation in yard long bean. There was positive influence in nodulation by the progressive additions of biochar @10 t ha^{-1} to 30 t ha^{-1} along with NPK (Rondon *et al.*, 2007)

Biochar can improve the biometric characters and crop performance directly as a result of its nutrient content and release characteristics, as well as indirectly, *viz.* (i) improved retention of nutrients (Lehmann *et al.*, 2003); (ii) improvements in soil pH (Rondon *et al.*, 2007); (iii) increased soil CEC (Liang *et al.*, 2006); (iv) improved soil physical properties (Chan *et al.*, 2008), including an increase in soil water retention (Laird *et al.*, 2010); and (v) alteration of soil microbial populations and functions (Pietikainen *et al.*, 2000).

Biochar additions not only affect microbial populations and activity in soil, but also plant–microbe interactions through their effects on nutrient availability and modification of habitat (Giller, 2001). With large bio-char concentrations, available Ca, P, and micronutrient concentrations are high, which is ideal for maximum BNF (Lehmann *et al.*, 2003).

The larger pore volume in biochar acts as nutrient reservoir and microhabitat for the growth of beneficial microorganisms.

5. 3. 4. Effect of Treatments on Yield and Yield Attributes of Yard Long Bean

Biochar application significantly enhanced the yield and yield attributing characters of yard long bean (Fig. 22). The yield was increased by 54.32 per cent by the application of biochar @ 20 t ha^{-1}. The significantly superior yield of 20.12 t ha^{-1} was registered by the treatment to which biochar was applied @ 20 t ha^{-1} along with 2 per cent PGPR and NPK as per POP. Treatment that received POP recorded the lowest yield of 13.04 t ha^{-1}. Application of biochar @ 10 t ha^{-1} along with NPK increased the crop yield (18.70 t ha^{-1}) by 43.40 per cent, compared to the control treatment. There was progressive increase in yield and yield attributing characters as the levels of biochar increased from 10 to 30 t ha^{-1} when it was applied with NPK. Treatment that received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP showed an enhancement in yield by 12.51 per cent, compared to the the treatment that received biochar @ 20 t ha^{-1} along with NPK as per POP.

Pod yield per plant also followed the same trend. As a result of biochar application, there observed an improvement in pod length by 20.31 per cent (54.50 cm), pod girth by 36.84 per cent (3.90 cm), mean pod weight by 18.04 per cent (26.63 g) and number of pods per plant by 30.77 per cent (51), compared to the control treatment that had not received biochar.

The higher yield of plants observed during the experiment by biochar application could be assigned to the increased soil pH as a result of liming effect, improved WHC, increased CEC, enhanced BNF, reduced leaching loss of nutrients especially N in to the ground water and that of P in to surface waters, reduced bulk density of soil and its high surface area providing a medium for adsorption of plant nutrients, enhanced nutrient uptake by plants and improved conditions for the multiplication and activity of soil micro-organisms.

A liming effect of biochar has been suggested as one of the likely reasons for improved crop yields on acidic soils (Verheijen *et al.*, 2010). Improved crop yields have also been attributed to a 'fertilizer effect' of added biochar supplying all the essential plant nutrients.

Cheng *et al.* (2006) reported that the shift from an acidic environment towards a more neutral pH through biochar additions increases CEC. Carrots and beans grown on steep slopes and on soils with a soil reaction of pH less than 5.20 had yields significantly improved by bio-char additions (Rondon *et al.*, 2005).

Lehmann and Rondon (2006) reviewed 24 studies with soil biochar additions and found improved productivity in all of them ranging from 20 to 220 per cent at application rates of 0.40 to 8.00 t ha^{-1} C. Such increases in productivity were explained by improving soil chemical, biological and physical properties.

Lehmann (2007) stressed that nutrients of the soil are retained and remain available to plant due to the application of biochar hence it increased crop yield. Moreover, it resulted in better uptake of nutrients, better partitioning of photosynthates, enhanced pod length, pod girth, number of pods per plant and finally the pod yield. The synergistic effect of biochar and mineral fertilizer is thought to be the result of increased plant nutrient uptake to leaching ratio and improved availability of cationic nutrients such as P, K, Ca and Cu (Lehmann *et al.*, 2003). This synergistic effect may be more prevalent in tropical regions, where Steiner *et al.* (2007) reported an increase of maize grain yield by 50 per cent relative to a fertilized control when 11 t ha^{-1} of biochar plus 85 kg N ha^{-1} of mineral fertilizer were applied to a highly weathered Xanthic Ferralsol. Alburquerque *et al.* (2013) reported that addition of wheat straw biochar @ 2.50 per cent led to about 20 to 30 per cent increase in grain yield compared with the use of the mineral fertilizer alone.

Major *et al.* (2010a) reported that biochar application @ 20 Mg ha^{-1} incresaed the maize yield in the second, third and fourth year by 28, 30 and 140 per cent respectively, compared to controls. Compared to the treatment without biochar, the biochar application significantly enhanced the cob length by 11 to 16 per cent, cob diameter by 5 to 9 per cent and weight of 1000 grains by 2 to 6 per cent.

In addition to this, application of PGPR had also played significant role in improving growth and yield of yard long bean. Yield increase obtained in inoculated plants could be attributed to the production of plant growth promoting substances produced by root colonizing bacteria (Kennedy and Tchan, 1992). These might be responsible for well developed root system and enhanced nutrient and water uptake, thereby overall promotion of yield. The results of the present study are in close conformity with those reported by Yadegari *et al.* (2008) who found a significant increase in pods plant^{-1}, number of seeds pod^{-1}, weight of 100 seeds, weight of seeds plant^{-1} and protein content by co-inoculation of PGPR and Rhizobium in beans.

Similarly, desirable effects of various inoculations in legumes reported in many experiments (Sindhu *et al.*, 2002) could be assigned to increased nutrient uptake and other plant growth promoting traits. Beck (1991) had shown that biochar is a suitable carrier for the N_2-fixing root nodule bacteria *Rhizobium*, *Mesorhizobium* and *Bradyrhizobium* and this promoted crop yield. Saranya *et al.* (2011) also reported that coconut shell based biochar was found to increase the survival of *Azospirillum lipoferum* upto (6 months).

Saxena *et al.* (2013) conducted a pot culture experiment to study the impact of addition of biochar along with *Bacillus* sp. on growth and yield of french beans, and observed that addition of biochar @ 15 g kg^{-1} of soil along with commercial biofertilizer (Biozyme) resulted in obtaining the highest number of phosphate solubilizing bacteria in the rhizosphere of plants and percent N content in shoots. The root length and root and shoot biomass were significantly higher 14.88 cm, 1.85 g and 3.22 g, respectively in the treatment consisting of soil, biochar and *Bacillus* sp. as compared to 10.68 cm, 0.89 g and 1.62 g in uninoculated control.

Biochars are generally low in inorganic-N and this can provide diazotrophs with a competitive advantage for colonization of the biochars large surface area. This factor combined with biochar's potential for NH_4^+ exchange with the soil solution and its ability to adsorb NH_4^+ effectively could modify soil-

N availability to the plant and stimulate nodulation and fixation. A role has been suggested for biochar in adsorbing and protecting chemical signalling molecules derived from plants such as the nod factors which enhance root nodulation via *Rhizobia* (Thies and Rillig, 2009).

PGPR have been extensively documented for their positive impact on plants, and if added with biochar, they not only result in an enhancement of crop yield, but also help in preventing fertilizer run-off, leaching, retaining moisture and helping plants through periods of drought. Most importantly, the combination of PGPR and biochar replenishes exhausted or marginal soils with organic carbon and fosters the growth of soil microbes essential for nutrient mineralization and absorption.

TDM production was profoundly improved by 51. 36 per cent in T_8 (biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP) which recorded significantly superior TDM production, followed by T_4 which received biochar @ 30 t ha^{-1} + NPK as per POP and the treatment which received POP recorded the least value. In addition to this, the Harvest Index was found to be increased by 15.79 per cent. These results are in conformity with the results obtained by Vaccari *et al.* (2011) who found out that application of 30 t biochar ha^{-1} combined with annual fertilization of 122 kg N ha^{-1} resulted in 21.00 per cent dry matter increase in wheat. The better availability, uptake and assimilation of nutrients facilitated by biochar increased the vegetative growth and thus resulted in increased dry matter production also.

The HI and B: C ratio was also found to be significant by the application of treatments. The significantly highest HI and B: C ratio were obtained for the treatment T_8 (biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP) which recorded the maximum yield. Major *et al.* (2010a) reported that biochar application @ 20 t ha^{-1} improved the HI in wheat.

5. 3. 5. Pod Protein

The experimental results revealed that the highest crude protein in pod was recorded by the treatment that received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP, followed by T_4 (biochar @30 t ha^{-1}+ NPK as per POP). There observed an increase by 54.67 per cent and 14.38 per cent in the pod protein content by the application of T_8 and T_4 respectively (Fig. 24). The better nodulation facilitated by biochar application might have promoted better uptake, accumulation and assimilation of N in plant parts especially in pods and hence increased dry matter production and the N content in pod. The aminoacid production and protein formation also might have been raised. All these favorably influenced the pod protein content also by the application of biochar.

5. 3. 6. Effect of Treatments on Nutrient Content in Pod, Shoot and Total Uptake of Nutrients

5.3.6.2. Nutrient Content in Pod

The N content in pod was significantly influenced by the application of biochar and pods in treatment T_8 were significantly superior in N content (3.30 per cent), followed by T_4 (3.20 per cent) which received biochar @ 30 t ha^{-1} + NPK as per POP and there observed an increase by 49.13 per cent and 41.51 per cent increase at fifter per cent flowering stage and at final harvest stage (Fig. 23). Eventhough the N availability in soil was superior for the treatment T_4 which received biochar @ 30 t ha^{-1} + NPK as per POP (296.75 kg ha^{-1}), T_8 was on par with that treatment (295.45 kg ha^{-1}). Better nodulation and BNF in T_8 favoured the improved N uptake and pod N content. In addition to changing nutrient availabilities that are conducive to high BNF, inoculation with Rhizobia (PGPR) may be more effective in presence of bio-char due to the habitat offered by the bio-char. In fact, several studies indicate that bio-char is an excellent support material for Rhizobium inoculants (Lal and Mishra, 1998). Availability of Fe and Mn in soil was also superior for T_8 (Table 34) and, if these two nutrients are sufficiently available, free-living N fixers could be favoured on and in biochar particles. Biochars are generally low in inorganic-N and this can provide

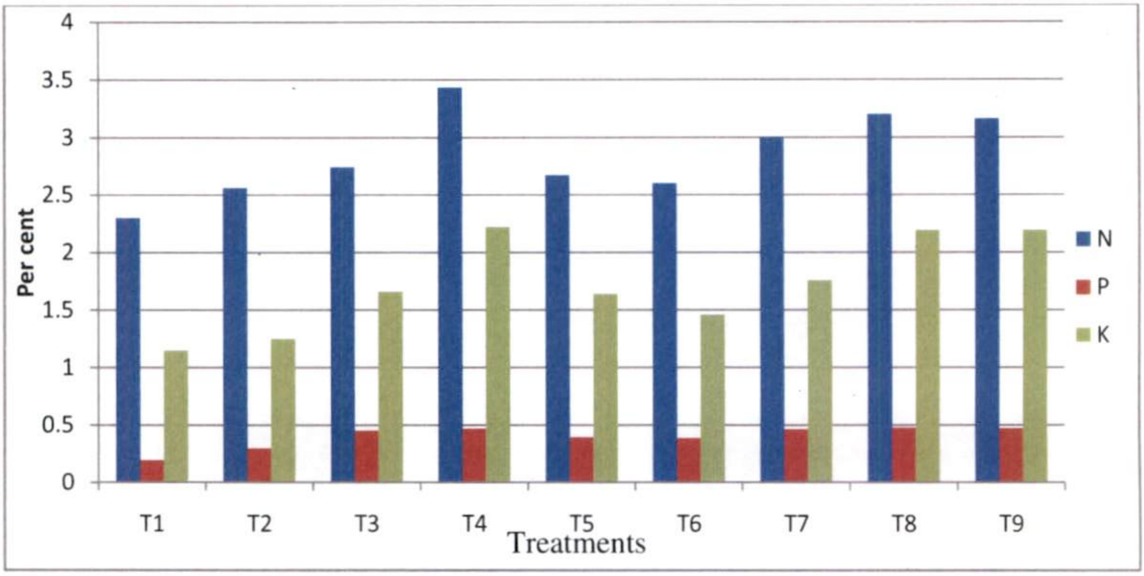


Fig. 23. Effect of treatments on content of N, P and K in pod

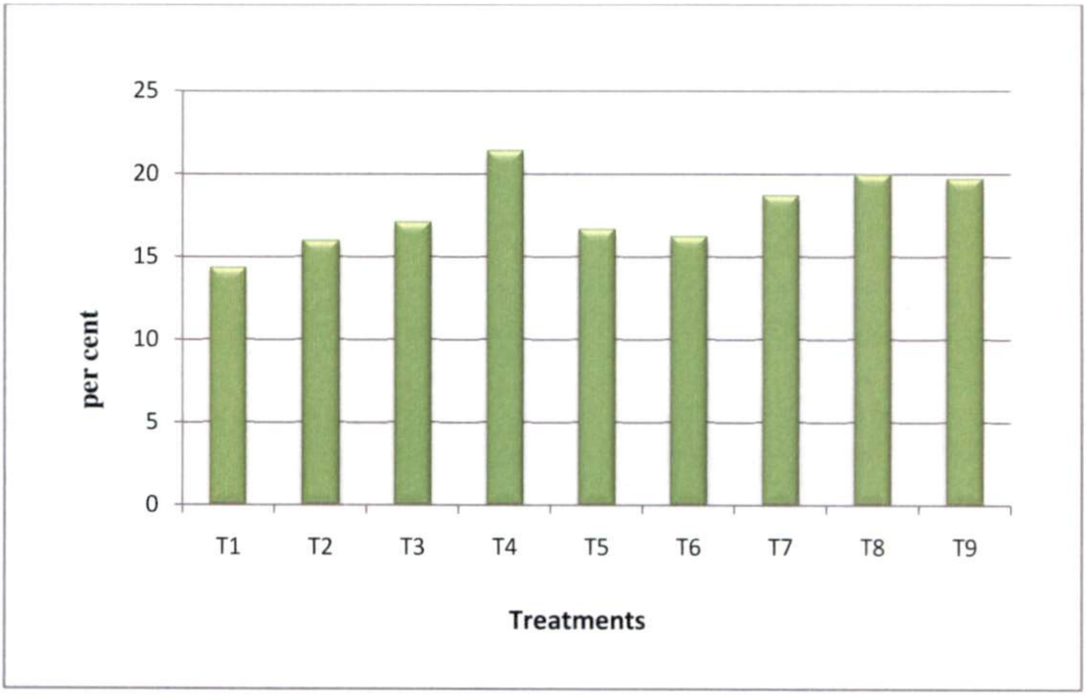


Fig. 24. Effect of treatments on pod protein content

diazotrophs with a competitive advantage for colonization of the biochars large surface area. This factor combined with biochar's potential for NH_4^+ exchange with the soil solution could modify soil-N availability to the plant and stimulate nodulation and fixation. (Thies and Rillig, 2009).

Regarding P content in pod, the significantly superior value of 0.478 per cent was registerd by the treatment that received T_9 (biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP) and it was on par with T_8 (biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP) which recorded the P content of 0.474 per cent. There observed significant improvement in pod P content by biochar application along with microbial consortium *viz.* AMF and PGPR (Fig. 24). That might be due to the better solubilization of P by the secretion of organic acids like citric, fumaric, tartaric and keto- butyric acids produced by beneficial microorganisms in AMF which in turn increased the availability of P in soil that resulted in improved P uptake and P content in pod.

Pod K content was significantly superior for T_4 which received biochar @ 30 t ha^{-1} + NPK as per POP (2.22 per cent) and it was on par with T_8 and T_9. There observed an enhancement by 93.04 per cent and 90.43 per cent regarding K content in pod at fifty per cent flowering and final harvest stages of the crop respectively (Fig. 24). This might be due to the better K content (2.27 per cent) in biochar which resulted in an increase in K availability in soil as a result of biochar application. This in turn amplified the K content in pod.

Ca content in pod was the highest for T_8 (biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP) which recorded the value of 2. 32 per cent which was 92.00 and 39.42 per cent respectively higher compared to the control treatment that received POP. Biochar application @ 30 t ha^{-1} also registered the comparable results. The high Ca content in pod is attributed to the relatively high Ca content in biochar and its ability to sorb Ca^{2+}on its surface because of its high CEC and this resulting in reduced leaching of this nutrient and improved uptake. Regarding Mg content in pod, the significantly superior value of 0.296 per cent was registered for the treatment that received T_8 (biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP) and there observed an improvement by 50.25 per cent, when compared to the control treatment that received POP. S content was also superior for T_8 which recorded the value of 0.187 per cent and the per cent increase was 61.21 per cent, compared to control.

Fe and Mn contents in pod were highest for the treatment T_8 that received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP both at fifty per cent flowering stage and at final harvest stage.

The content of Zn in pod was increased by the application of biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP and the per cent increase obtained was 78.06 per cent and 68.44 per cent at fifty per cent flowering final harvest stages of the crop. T4 was found to be on par with T_8 in the case of Zn content in pod at fifty per cent flowering stage.

Regarding Cu content in pod there observed an increase by 76.83 per cent and 82.03 per cent at fifty per cent flowering and final harvest stage when biochar was applied @20 t ha^{-1} along with 2 per cent PGPR and NPK as per POP.

The high pod nutrient content in the biochar treated plots is attributed to the increased availability of the nutrients in soil that resulted in better utilization, improved uptake by the crop and efficient partitioning of nutrients to pods.

5.3.6.2. Nutrient Content in Shoot

The content of N in shoot was also highest for T_8 (biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP). The N content was increased by 38 per cent at fifty per cent flowering stage and 52.50 per cent at final harvest stage of the crop, when compared to the control (POP). Saxena *et al.* (2013) reported that application of biochar @ 15 g kg^{-1} along with *Bacillus* improved the P content in shoot from 1.14 per cent to 1.64 per cent.

The P content of shoot due to various treatments is presented in Fig. T_9 which received biochar @ 20 t ha^{-1} + AMF @ 200 g m^{-2} + NPK as per POP recorded the significantly superior and there observed an increase by 55.34 and 61.11 per cent respectively at fifty per cent flowering stage and at final harvest stage of the crop. Saxena *et al.* (2013) reported that application of biochar @ 15 g kg^{-1} along with *Bacillus* improved the P content in shoot from 0.583 to 0.683 per cent.

Statistical analysis of the data indicated that K content in shoot was increased by 81.54 per cent and 91.89 per cent respectively at fifty per cent flowering and at final harvest stage of the crop in the treatment T_8, compared to the control treatment.

Regarding content of Ca in shoot, T_8 registered a significant increase in Ca content by 1.28 per cent to 2.87 per cent. Biochar application @ 30 t ha^{-1} also registered the comparable results. Major *et al.* (2010a) observed an improvement in Ca content from 1.08 to 1.36 g kg dry $matter^{-1}$ for maize leaf samples taken at tasseling stage by the application of biochar @ 20 t ha^{-1}.

Biochar application radically improved Mg content in shoot both at fifty per cent flowering and at final harvest stage and there observed an increase by 67.53 and 64.62 per cent respectively. The result is in conformity with those obtained by Major *et al.* (2010a) who observed an enhancement in Mg content in maize leaf from 0.92 to1.03 g kg dry $matter^{-1}$ when biochar was applied @ 20 t ha^{-1}.

Regarding S content in shoot, T_8 recorded the superior value of 0.37 per cent and there observed an increase by 92.11 per cent and 93.14 per cent respectively at fifty per cent flowering and final harvest stage. The high nutrient status in soil naturally improved the uptake of S by the crop.

Fe content in shoot was significantly superior for the treatment that received T_8 both at fifty per cent flowering and final harvest stage. The data on content of Mn in shoot presented in Fig revealed that there was significant variation due to treatments. A close scrutiny of the mean value indicated an increase in Mn concentration in shoot by 26.22 per cent and 26.12 per cent at fifty per cent flowering and at final harvest stage by the application of biochar.

Application of biochar @ 30 t ha^{-1} also registered the similar results and it was found to be on par with T_8 in the case of Mn content at fifty per cent flowering stage.

Zn content in shoot was increased by 69 per cent at fifty per cent flowering stage and by 59.33 per cent at final harvest stage, when compared to POP and the significantly superior value was shown by the treatment T_8 which received biochar @ 20 t ha^{-1} + 2 per cent PGPR + NPK as per POP. Biochar @ 30 t ha^{-1} registered the comparable values at fifty per cent flowering stage.

By the application of biochar, the Cu content in shoot was significantly improved by 107.71 per cent and 78.03 per cent respectively at ffity per cent flowering stage and at final harvest stage of the crop. Application of biochar @ 30 t ha^{-1} also registered the similar results.

5.3.6.3. Total Uptake of Nutrients

Total uptake of all the nutrients was found to be significantly superior for T_8 to which biochar was applied @ 20 t ha^{-1} along with 2 per cent PGPR and NPK as per POP (Fig. 25, Fig. 26).

The total uptake of N was found to be increased from 51.19 kg ha^{-1} to 105.50 kg ha^{-1}. Regarding P uptake, there observed an increase from 4.73 to 14.17 kg ha^{-1}. The better K content (2.27 per cent) in biochar which resulted in an increase in K availability in soil as a result of biochar application. This in turn amplified the K uptake by 194.17 per cent compared to the control treatment that did not receive biochar (POP). The elevated K uptake is due to the fact that the reduction in leaching losses and thus the increased availability of nutrient in soil (Chan *et al.*, 2007; Yamato *et al.*, 2006).

By the application of biochar, the total uptake of Ca was found to be increased from 26.73 to 61.03 kg ha^{-1}, compared to the control treatment. The total uptake (10.67 kg ha^{-1}) of Mg was found to be increased by 123.68 per cent in T_8, compared to the treatment that received POP due to the increased available Mg status of biochar applied plots. Regarding S, the total uptake was enhanced

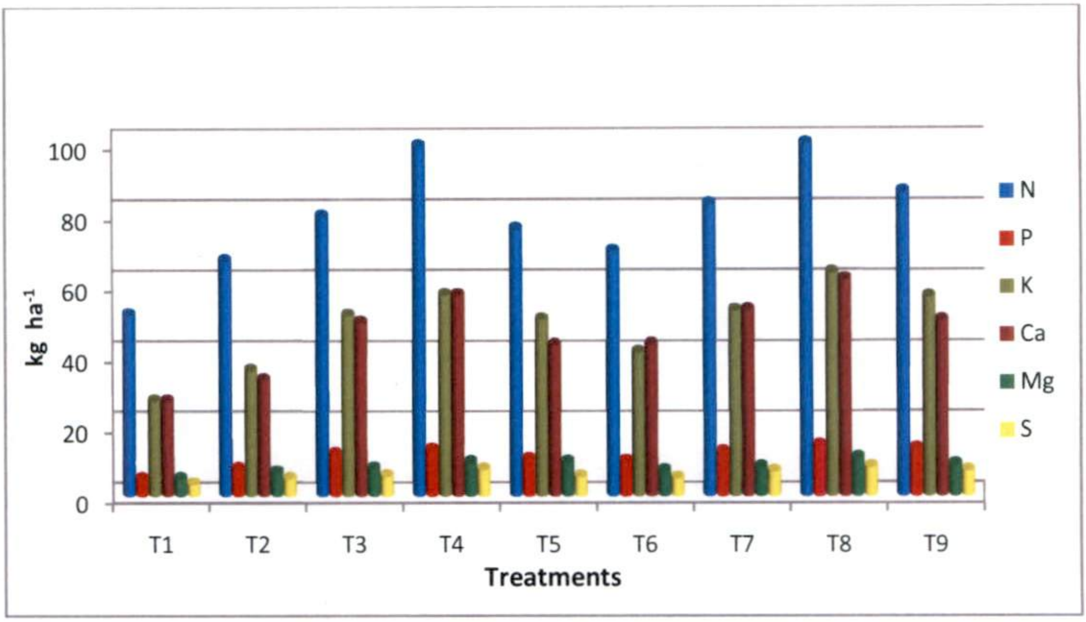


Fig. 25. Effect of treatments on total uptake of N, P, K, Ca, Mg and S by yard long bean

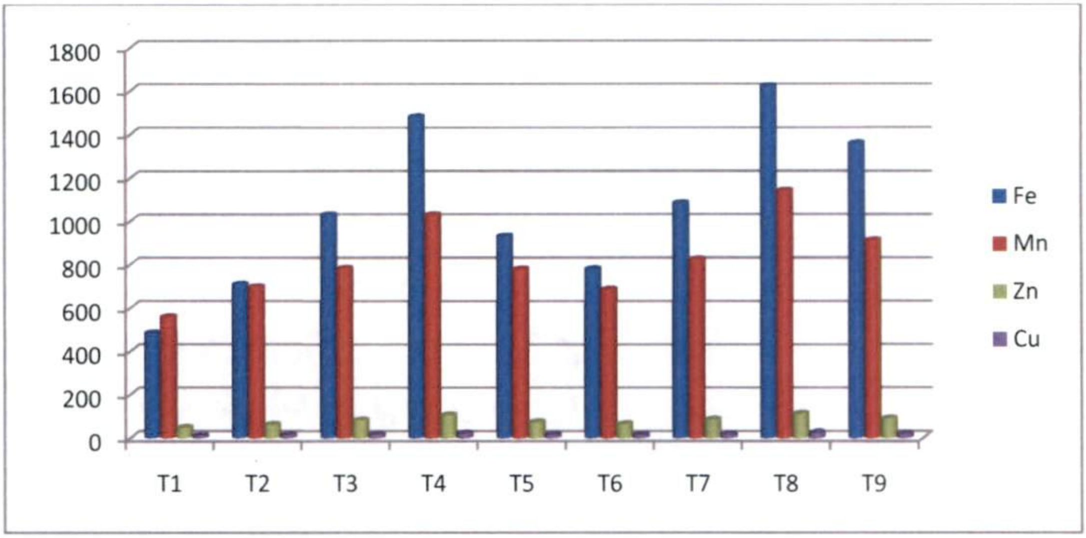


Fig. 26. Effect of treatments on total uptake of Fe, Mn, Zn and Cu by yard long bean

from 3.28 to 7.99 kg ha^{-1} for the treatment that received @ 20 t ha^{-1} along with 2 per cent PGPR and NPK as per POP, compared to POP.

Regarding the total uptake of micronutrients, Fe uptake was found to be increased from 482.63 to 1623 g ha^{-1} and that of Mn was increased from 559.31 to 1140.50 g ha^{-1}. The Zn uptake was also superior for the treatment to which biochar was applied @ 20 t ha^{-1} along with 2 per cent PGPR and NPK as per POP and there observed an improvement from 2.43 to 5.57 g ha^{-1} and in the case of Cu uptake, the observed improvement was 4.27 to 10.86 g ha^{-1}.

Yeboah *et al.* (2009) reported that application of 3 t ha^{-1} biochar + 120 kg N ha^{-1} enhanced the N uptake of from 66.85 to 71.69 kg ha^{-1}, K uptake from 9.55 to 15.36 kg ha^{-1}. Major *et al.* (2010a) observed an improvement in total uptake of K from 45.5 and 50.7 kg ha^{-1} by biochar application @ 20 t ha^{-1}. Alburquerque *et al.* (2013) reported that addition of wheat straw biochar @ 2.50 per cent led to increased Zn and Cu uptake and olive tree pruning biochar improved the P and Mg uptake. An improvement in N uptake from 3.20 to 20.50 mg by biochar from papermill waste was reported by Van Zwieten *et al.* (2010a).

As a result of biochar application, there was improved availability of all the essential plant nutrients in soil which further resulted in enhancement of their uptake of the respective nutrients by the crop. Improved uptake and better partitioning of nutrients resulted in enhancing the concentration of the respective nutrients in shoot and pod. Hence, application of biochar in soil can improve the nutritional quality of yard long bean, increases crop yield, alleviates poverty and helps in achieving food security.

From the results of the field experiment, it can be concluded that yield (20.12 t ha^{-1}) and yield attributes like pod length (54.50 cm), pod girth (3.90 cm), number of pods per plant (51), content of nutrients in pod, nutrient uptake and B: C ratio were significantly superior for the treatment T_8 which received biochar @ 20 t ha^{-1} with 2 per cent PGPR and NPK as per POP. T_8 can be considered as the economically viable and the best treatment with a yield of 20.12 t ha^{-1}. There was progressive improvement in the physical, elecro-chemical and chemical properties of soil by increasing the quantity of biochar applied from 10 to 30 t ha^{-1}. Conversion of biomass to biochar is a cost effective way for waste management (tender coconut husk) in the humid tropics. Biochar is a rich source of C and all the essential plant nutrients, efficient releaser and adsorber of nutrients, a potential tool for carbon sequestration and finally a best soil amendment which can improve physical, chemical and biological properties of soil to a great extent and crop yield.

Table 51. Comparison between control treatment and the best treatment

Parameters	Control	Best treatment	Per cent increase or decrease
Liming effect (pH)	4.93	6.36	29.00
CEC	3.14	5.13	63.38
WHC (per cent)	30.89	40.67	31.66
Bulk density (Mg m^{-3})	1.32	1.20	9.00 (decrease)
WSC (per cent)	56.78	79.86	40.65
Organic C (per cent)	0.79	1.32	67.09
CO_2 emission (mg ha^{-1})	5922.90	920.40	84.46
Yield (t ha^{-1})	13.04	20.12	54.29

Hence, biochar production from tender coconut husk and its use as soil amendment can be used as a means of abating climate change by sequestering C, while simultaneously reducing waste; improving soil quality and enhancing crop quality and yield. This will help in restoring soil health and attaining food security.

Summary

6. SUMMARY

Detailed investigations consisting of production of biochar from tender coconut husk and its characterization, laboratory experiments *viz.* nutrient sorption-desorption studies; carbon dioxide emission studies and a field experiment to assess the effects of biochar on soil properties, growth and yield of crops using yard long bean (*Vigna unguiculata* subsp. *sesquipedalis*) as the test crop were carried out in Loamy Skeletal Kaolinitic Isohyperthermic Rhodic Haplustult at College of Agriculture, Vellayani during 2011 to 2014. The results of the study are summarized below:

- Biochar was produced from tender coconut husk by indigenous method, using fabricated biochar production unit ('Biochar kiln') and the process was slow pyrolysis at a temperature of 350^{O}C to 400°C. From 30 kg tender coconut husk, 10 kg biochar was produced within 1.50 h.
- The biochar produced was having an alkaline pH (9.13). The tender coconut husk biochar had an EC of 1.73 dS m^{-1}, CEC of 15.26 cmol (+) kg^{-1} and total C content of 72.30 per cent. It was a rich source of nutrients with N (1.05 per cent), P (0.38 per cent), K (2.27 per cent), Ca (0.40 per cent), Mg (0.29 per cent) and S (0.27 per cent). 123.04 mg kg^{-1} Fe, 16.50 mg kg^{-1} Mn, 21.09 mg kg^{-1} Zn and 3.98 mg kg^{-1} Cu were also present in biochar.
- Tender coconut husk biochar recorded the C: N ratio of 68.86 whereas tender coconut husk registered a value of 66.52. The produced biochar had promising characteristics like water holding capacity of 226 per cent, bulk density of 0.14 Mg m^{-3}, BET surface area of 157.93 m^2 g^{-1}, Langmuir surface area of 237.81 m^2 g^{-1}, micropore area of 110.83 m^2 g^{-1}, external surface area of 47.10 m^2 g^{-1} and micropore volume of 0.06 cm^3 g^{-1}.
- Desorption experiments using biochar revealed that when biochar was equilibrated with de-ionized water in 1:100 ratio, the pH of the rinse solution was

stabilized to 9.20 after 72 h of shaking. After each rinse, the concentration of nutrient in the solution phase was found to be increased that resulted in a decrease in the initial concentration of the nutrient in biochar.

- Biochar from tender coconut husk (1 kg) could desorb 3386.25 mg NH_4^+, 2858.44 mg PO_4^{3-}, 10226.35 mg K^+, 1840 mg Ca^{2+}, 676 mg Mg^{2+}, 2019.87 mg SO_4^{2-}, 45.16 mg Fe^{2+}, 4.96 mg Mn^{2+}, 5.62 mg Zn^{2+}, 1.06 mg Cu^{2+} within 3 days when it was equilibrated with de-ionized water in 1:100 ratio. Anions like PO_4^{3-} (75.62 per cent) and SO_4^{2-} (74.26 per cent) were desorbed at a higher rate than cations and the lowest per cent of nutrients desorbed were Zn^{2+} and Cu^{2+} (26.67 per cent).
- The sorption experiments using biochar revealed that, 100 mg of NH_4^+, 90.70 mg of PO_4^{3-}, 92.00 mg of K^+, 87.00 mg of Ca^{2+}, 86.15 mg of Mg^{2+}, 91.82 mg of SO_4^{2-}, 49.84 mg of Fe^{2+}, 50.00 mg of Mn^{2+}, 49.56 mg of Zn^{2+} and 49.56 mg of Cu^{2+} were found to be sorbed on 1 kg biochar within 24 h when it was equilibrated with 100 mg l^{-1} of the respective nutrient solutions.

During the course of time, the per cent of nutrients sorbed on biochar also increased. The quantity of nutrient sorbed was higher at lower concentrations of nutrients and as the concentration of nutrients increased, Subsequent increase in sorption of nutrients was found to be less. In addition to this, anion adsorption was lesser compared to cation adsorption.

- Overall, the laboratory experiments showed that the nutrient (especially cations) adsorption power of biochar is high. Once biochar is added to an agricultural field as a soil amendment, it will efficiently prevent nutrients from leaching during runoff by adsorption and make them available to plants through desorption. Therefore, it can be concluded that biochar as a soil amendment is a good adsorber and slow releaser of nutrients and its application can reduce chemical fertilizer use.
- Biochar application had significant influence on reducing CO_2 emission, compared to other organic amendments like FYM and vermicompost. The maximum emission was recorded by FYM application @ 2 per cent level in soil followed by T_3

which received FYM @ 1 per cent and the lowest emission was recorded by biochar @ 1 per cent level.

- The total emission was found to be reduced by 86.64 per cent and 48.11 per cent when the soil was incubated with biochar @ 2 per cent, compared to the treatment that received FYM @ 2 per cent and vermicompost @ 2 per cent respectively.
- Comparing different levels of biochar used, the lowest emission was registered by the treatment that received biochar @ 1 per cent, followed by biochar @ 2 per cent. In treatments receiving biochar, the emission was low compared to other treatments, except control.
- The order of emission is as follows: control < biochar @ 1 per cent < biochar @ 2 per cent < vermicompost @ 1 per cent < vermicompost @ 2 per cent < FYM @ 1 per cent < FYM @ 2 per cent.
- WHC of the soil increased from 30.89 per cent (POP) to 48.78 per cent by the application of biochar @ 30 t ha^{-1} along with POP (T$_4$) and there observed an increase of 57.92 per cent in WHC of the soil at the experimental site. When biochar was applied @ 20 t ha^{-1} along with 2 per cent PGPR and NPK as per POP (T$_8$), the WHC increased by 31.66 per cent.
- T$_4$ (BC$_{30}$+ NPK) and T$_8$ (BC$_{20}$ + PGPR + NPK) were found to be on par in the case of porosity of the soil, and significantly increased the porosity by 21.22 per cent and 19.66 per cent at fifty per cent flowering stage.
- Bulk density of the soil was reduced by by 9.09 per cent at fifty per cent flowering stage by the application of BC$_{30}$+ NPK and it was also on par with BC$_{20}$ + PGPR + NPK.
- The soil pH was found to be incrreased from 4.93 to 6.57 and 6.36 with the application of T$_4$ (BC$_{30}$+ NPK) and T$_8$ (BC$_{20}$ + PGPR + NPK) respectively.
- The initial soil had CEC of 2.56 cmol kg^{-1}. At 50 per cent flowering stage, T$_4$ (BC$_{30}$+ NPK) registered the significantly superior value of 5.43 cmol kg^{-1}, which was on par with T$_8$ (5.13 cmol kg^{-1}) that received BC$_{20}$ + PGPR + NPK. The

improvement of the CEC by 72.93 per cent (T_4) and 63.38 per cent (T_8) can be attributed to the high SSA of biochar, which resulted from its porous structure. The lowest value was registered by POP.

- The organic C content was significantly increased from 0.79 per cent to 1.43 per cent when BC was applied @ 30 t ha^{-1} along with POP and it was on par with T_8 to which BC was applied @ 20 t ha^{-1} along with 2 per cent PGPR + NPK (1.32 per cent) and T_9 to which BC was applied @ 20 t ha^{-1} along with AMF @ 200 g m^{-2} + NPK (1.27 per cent).
- Regarding the availability of N, K, Ca and Mg in soil, T_4 (BC_{30} + NPK) was found to be on par with T_8 (BC_{20} + PGPR + NPK) and T_9 (BC_{20}+ AMF @ 200 g m^{-2} + NPK).
- Available P status in soil was superior for the treatment that received T_9 (BC $_{20}$+ AMF @ 200 g m^{-2} + NPK) followed by T_8 which received BC_{20} + PGPR + NPK and the lowest value was recorded by the POP treatment.
- Available S, Fe, Mn, Zn and Cu status in soil were significantly superior for the treatment T_8 that received BC_{20} + PGPR + NPK.
- Regarding total emission of carbon dioxide in field, the lowest emission was observed for the treatment T_2 that received the lowest rate of biochar (10 t ha^{-1}) along with NPK, followed by biochar @ 20 t ha^{-1}. Hence, biochar application can significantly reduce CO_2 emission and can be used as an efficient tool for carbon sequestration.
- The results of the field experiment revealed that all the physical, chemical and electro-chemical properties were significantly improved by the application of biochar.
- The content of N in shoot and pod were significantly superior for the treatment that received T_8 (BC_{20} + PGPR + NPK).. Significantly superior value for P content was recorded by the combined application of BC @ 20 t ha^{-1}, AMF @ 200 g m^{-2} and NPK as per POP, and it was found to be on par with T_8 (BC_{20} + PGPR + NPK)..

- Pod K content was significantly superior for T_4 which received biochar @ 30 t ha^{-1} + NPK as per POP (2.22 per cent) and it was on par with T_8 and T_9.
- Ca content in pod was the highest for T_8 (BC_{20} + PGPR + NPK) which recorded the value of 2. 32 per cent which was 92.00 per cent and 39.42 per cent respectively higher compared to the control treatment that received POP. Biochar application @ 30 t ha^{-1} also registered the comparable results.
- Content of Mg, S, Fe, Mn, Zn and Cu in shoot and pod were significantly increased by the application of biochar..
- The total uptake of N, P, K, Ca, Mg, S, Fe, Mn, Zn and Cu by the crop were enhanced by the application of BC_{20} + PGPR + NPK. The highest crude protein (21.44 per cent) was recorded by the treatment T_8, followed by T_4.
- In the present study, application of biochar @ 20 tha^{-1} along with 2 per cent PGPR and NPK as per POP (T_8) resulted in having lesser number of days for first flowering, fifty per cent flowering and the crop duration was also significantly highest for T_8. Vine length (517.50 cm), number of leaves (240) per plant, number (18) and weight of nodules per plant (1.95) were significantly superior for that treatment, followed by T_4 (BC_{30}+ NPK).
- As a result of biochar application BC @ 20 t ha^{-1} along with 2 per cent PGPR and NPK along with NPK as per POP (T_8), there observed an improvement in the pod length by 20.31 per cent (54.50 cm), pod girth by 36.84 per cent (3.90 cm), mean pod weight by 18.04 per cent (26.63 g) and number of pods per plant by 30.77 per cent (51) compared to the control treatment that had not received biochar. Mixing biochar with beneficial microbial consortium like PGPR mix 1 has an additive effect on nutrient availability and plant growth.
- Application of biochar @ 20 t ha^{-1} along with 2 per cent PGPR and NPK as per POP (T_8) recorded the significantly superior yield of 20.12 t ha^{-1} with B: C ratio of 1.56 and it can be considered as the economically viable and the best treatment, followed by T_4 with an yield of 18.70 t ha^{-1} and B: C ratio of 1.46.

Tender coconut husk is a hard waste with high lignin content and a rich source of nutrients. There is additive effect if biochar is mixed with a consortium of beneficial microorganisms like PGPR mix-1 because biochar with its high surface area and pore volume will help for the better proliferation and activity of beneficial microorganisms in soil. Hence, application of biochar @ 20 t ha^{-1} with 2 per cent PGPR mix-1 and NPK as per POP resulted in better soil properties and yield.

Biochar is a rich source of C and all the essential plant nutrients, efficient releaser and adsorber of nutrients, a potential tool for carbon sequestration, one of the best way to utilize biowaste, to protect the environment safely and finally an excellent soil amendment. Combining biochar with organic and inorganic nutrient sources and microbial inoculants can sustain soil health and improve crop yield.

From the investigations, without any doubt, it was proved that application of biochar from tender coconut husk can enhance soil health, C sequestration, reduce land degradation, improve crop quality andyield, and thus biochar is one of the best way to utilise biowaste for attaining food security .

FUTURE LINE OF WORK

Conversion of biowaste to biochar by the process of pyrolysis is the most intelligent way of recycling organic waste and to reduce environmental pollution. During biochar production, syngas and bio-oil are produced that can be used as bioenergy source, which can solve the problems of energy crisis. Syngas can be utilized as cooking gas and as an alternate fuel for diesel engines.

Further study is required to synthesize biochar from different feed stocks and at different pyrolysis conditions, characterization and comparison of properties of the produced biochar materials. Also, it would be useful to assess the impact of biochar amendment on different crops and cropping systems. Enrichment of biochar at higher application rates (more than 30 t ha^{-1}) with nutrients (organic or inorganic) and beneficial microbial consortium and its application in soil will be an efficient approach for recycling of nutrients.

The present investigation show that while biochar has potential as a tool to reduce GHG emissions from soil, more research is required to understand the mechanisms which underlie these processes, and to quantify the effects of biochar application on GHG emissions when different biochar materials produced from different feed stocks are added to different field soils and under different production systems.

The sorption-desorption study has shown that biochar is an effective ion adsorbent and it can greatly reduce the leaching of highly mobile nutrients from fertilizers in sandy soils. This will allow nutrients to be kept in the rooting zone, and therefore improve the efficiency of fertilizers. Further, adding biochar below the rooting zone of plants can aid in preventing or reducing the contamination of surface and ground waters by inorganic fertilizers. Biochar also warrants merit in using it as a protective layer in the soil below pit toilets or polluted sites with the aim of retarding nutrients from seeping into groundwater. Because of its high affinity for adsorbing cations, biochar can be utilized for bioremediating heavymetals and organic pollutants from the environment.

In view of the positive plant growth response obtained in this study, a long term field trial of biochar application to soils is a highly pertinent area for future research. This would better contribute to scientific knowledge on making sound recommendations on the use of biochar in a range of agricultural soils.

Research on the production, characterisation and application of biochar as a soil amendment in Kerala is a relatively new and therefore further research is necessary to build a strong scientific database and knowledge. This would greatly contribute to scientific literature in facilitating a clearer understanding of the changes in nutrient availability and soil reaction in soil over time as a result of addition of biochar to agricultural soils. Clearly, this highlights the importance of future research to establish the long-term effect of biochar application in soil.

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INVESTIGATIONS ON THE EFFICACY OF BIOCHAR FROM TENDER COCONUT HUSK FOR ENHANCED CROP PRODUCTION

by

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(2011-21-115)

Abstract of the
thesis submitted in partial fulfillment of the
requirements for the degree of

DOCTOR OF PHILOSOPHY IN AGRICULTURE

Faculty of Agriculture
Kerala Agricultural University

DEPARTMENT OF SOIL SCIENCE AND AGRICULTURAL CHEMISTRY
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VELLAYANI, THIRUVANANTHAPURAM- 695 522
KERALA, INDIA
2015

Abstract

ABSTRACT

An investigation was carried out at College of Agriculture, Vellayani to characterize biochar from tender coconut husk and to assess its effects on soil properties, growth and yield of yard long bean (*Vigna unguiculata* subsp. *sesquipedalis*). The experiment consisted of production and characterization of biochar, laboratory experiments on nutrient sorption- desorption studies, carbon dioxide emission studies and a field experiment.

Biochar was produced from tender coconut husk by the process of pyrolysis and it was crushed, sieved and the 2 mm sieved samples were used for further studies. The produced biochar had an alkaline pH (9.13), high CEC (15.26 cmol kg^{-1}) and C: N ratio (68.86). Electrical Conductivity, total C, N, P, K, Ca, Mg and S contents in the prepared biochar were 1.73 dS m^{-1}, 72.3 per cent, 1.05 per cent, 0.38 per cent, 2.27 per cent, 0.40 per cent, 0.20 per cent and 0.27 per cent respectively. The produced biochar recorded very high water holding capacity (226 per cent), low bulk density (0.14 Mg m^{-3}) and high Brunauer Emmett Teller surface area (157.93 m² g^{-1})

A laboratory experiment was conducted to study the desorption and sorption of nutrients like N, P, K, Ca, Mg, S, Fe, Mn, Zn and Cu using biochar. 32.35 per cent NH_4^+, 75.65 per cent PO_4^{2-}, 45.14 per cent K^+, 46.00 per cent Ca^{2+}, 23.45 per cent Mg^{2+}, 74.38 per cent SO_4^{2-}, 36.80 per cent Fe^{2+}, 30.20 per cent Mn^{2+}, 26.75 per cent Zn^{2+} and 26.72 per cent Cu^{2+} were found to be desorbed from biochar after 7 rinses using de-ionized water in 1:100 ratio. The highest per cent of nutrient desorbed was P (75.65 per cent), followed by S (74.38 per cent) and the lowest per cent of nutrients desorbed were Zn (26.75 per cent) and Cu (26.72 per cent) within 72 hours. Sorption experiments were performed using rinsed biochar at different concentrations of nutrients and at different time intervals in 1:100 ratio. The results of the study indicated that biochar could sorb 100 per cent NH_4^+, 90.70 per cent PO_4^{2-}, 92.00 per cent K^+, 87.00 per cent Ca^{2+}, 86.15 per cent Mg^{2+} and 91.82 per cent SO_4^{2-} when it was equilibrated with

100ppm solutions within 24hours. For micronutrients, when 50 mg l^{-1} Fe^{2+}, Mn^{2+}, Zn^{2+} and Cu^{2+} solutions were given, biochar could sorb 99.67 per cent, 100 per cent, 99.12 per cent and 99.12 per cent respectively. Biochar from tender coconut husk is a good sorber and slow releaser of nutrients.

An incubation study was carried out to estimate and study the pattern of carbon dioxide emission by the application of biochar into soil and it was compared with that of common organic amendments *viz.* FYM and vermicompost. The experiment consisted of 7 treatments with 3 replications and the study revealed that the cumulative amount of carbon dioxide emitted was highest for FYM @ 2 per cent (1014.05 mg CO_2 100 g^{-1}) and biochar @ 2 per cent registered an emission of 87.17 mg CO_2 100 g^{-1} after 6months of incubation. There observed 91.40 per cent reduction in CO_2 emission when soil was incubated with biochar @ 2 per cent compared to 2 per cent FYM.

A field experiment was carried out with biochar and other commonly used organic manures at different doses using yard long bean variety Vellayani Jyothika as the test crop during January 2013 to April 2013, at the Instructional farm, College of Agriculture, Vellayani. Yield (1358 g $plant^{-1}$) and yield attributes like pod length (54.50 cm), pod girth (3.90 cm), number of pods per plant (51), nutrient uptake and B: C ratio were significantly superior for the treatment T_8 which received biochar @ 20 t ha^{-1} with 2 per cent PGPR and NPK as per POP. Physical properties chemical properties of the soil were significantly improved by the application of biochar @ 30 t ha^{-1}. Biochar application reduced the bulk density, increased water holding capacity, water stable aggregates, pH, Cation Exchange Capacity, organic carbon status and nutrient availability.

From the investigations, it can be concluded that application of biochar @ 20 t ha^{-1} along with 2 per cent PGPR and NPK as per POP which resulted in the yield of 1358 g $plant^{-1}$ (20.12 t ha^{-1}) can be considered as the economically viable and the best treatment. Biochar from tender coconut husk can be used as a good soil amendment which can improve soil health and enhance crop production.

Appendix I

APPENDIX - I

Weather Data for the cropping period

(January 2013- April 2013)

Standard week	Temperature(^{0}C) (maximum)	Temperature (^{0}C) (minimum)	Rainfall (mm)	Relative Humidity (%)
1	30.6	23.4	8.8	95.4
2	30.0	22.6	24.0	96.4
3	30.1	20.8	0.0	96
4	30.5	21.3	0.0	96.1
5	30.4	20.8	0.0	94.3
6	30.2	22.9	21.0	93.3
7	30.0	23	15.0	92.4
8	30.4	21.8	0.0	89.9
9	30.0	21.4	0.0	91.3
10	30.1	24.3	7.0	94.7
11	30.3	23.9	34.0	93.4
12	30.3	23.7	0.0	91.4
13	30.5	23.3	31.0	92.7
14	32.9	26	0.0	92.7
15	32.8	25.6	1.5	89.9
16	33.2	25.1	0.0	84.8
17	33.3	25	20.3	87.0

Appendix II

APPENDIX – II

Report on surface area analysis of tender coconut husk biochar

Sample ID: Biochar Mariya dainy

Started: 8/19/3813 3:55:21PM
Completed: 8/19/3813 6:24:10PM
Report Time: 8/19/2013 6:17:53PM
Evac. Rate: 300.0 mmHg/min
Analysis Mode: Equilibration

Sat. Pressure: 791.89 mmHg
Freespace: None
Sample Weight: 0.1225 g
Evac. Time: 1.000000 minutes
Equil. Interval: 3 secs

Analysis Log

Relative Pressure	Pressure (mmHg)	Vol Adsorbed (cm³/g STP)	Elapsed Time (HR:MN)	Saturation Press. (mmHg)
				791.89001
0.099938120	79.14000	48.8041	01:10	
0.157042011	124.36000	50.5955	01:17	
0.214152223	169.58501	51.5563	01:22	
0.271199271	214.75999	52.3420	01:28	
0.328303181	259.98001	52.9527	01:31	
0.385407072	305.20001	53.3478	01:32	
0.442460441	350.38000	53.6845	01:34	
0.499690620	395.70001	54.0167	01:36	
0.556819753	440.94000	54.3669	01:37	
0.613967847	486.19501	54.6902	01:39	
0.671343236	531.63000	55.0314	01:41	
0.728396604	576.81000	55.3861	01:43	
0.785645744	622.14502	55.7588	01:44	
0.842869603	667.46002	56.0776	01:46	
0.899645115	712.41998	56.9486	01:48	
0.896866936	710.21997	57.9363	01:52	
0.842105555	666.85498	57.7522	01:53	
0.784755447	621.44000	57.6535	01:55	
0.727569509	576.15503	57.6400	01:56	
0.670465579	530.93500	57.6984	01:58	
0.613267001	485.64001	57.7702	02:00	
0.556314640	440.54001	57.8465	02:02	
0.499273874	395.37000	57.9049	02:03	
0.442599330	350.48999	57.6759	02:05	
0.385324987	305.13501	57.5861	02:07	
0.328214776	259.91000	57.5188	02:10	
0.271224532	214.78000	57.4155	02:12	
0.214202726	169.62500	57.2314	02:15	
0.157111466	124.41500	56.9486	02:20	
0.100001264	79.19000	56.4861	02:28	

APPENDIX – II

Report on surface area analysis of tender coconut husk biochar

Sample ID: Biochar Mariya dainy

```
     Started: 8/19/3813 3:55:21PM        Sat. Pressure: 791.89 mmHg
   Completed: 8/19/3813 6:24:10PM           Freespace: None
 Report Time: 8/19/2013 6:17:53PM        Sample Weight: 0.1225 g
  Evac. Rate: 300.0 mmHg/min                Evac. Time: 1.000000 minutes
Analysis Mode: Equilibration           Equil. Interval: 3 secs
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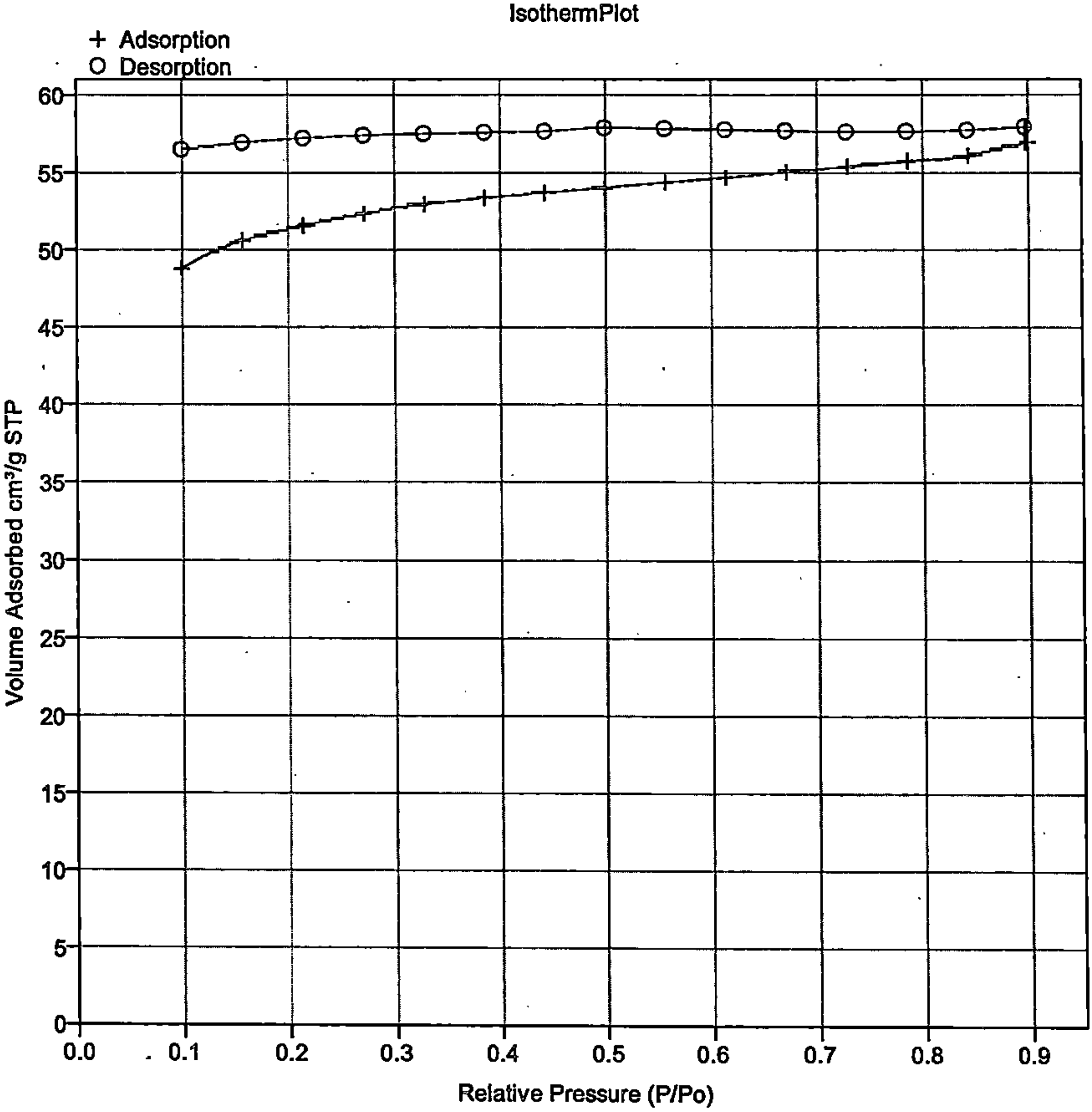


APPENDIX – II

Report on surface area analysis of tender coconut husk biochar.

```
Sample ID: Biochar Mariya dainy


     Started: 8/19/3813 3:55:21PM          Sat. Pressure: 791.89 mmHg
   Completed: 8/19/3813 6:24:10PM              Freespace: None
 Report Time: 8/19/2013 6:17:53PM          Sample Weight: 0.1225 g
  Evac. Rate: 300.0 mmHg/min                  Evac. Time: 1.000000 minutes
Analysis Mode: Equilibration             Equil. Interval: 3 secs
--------------------------------------------------------------------

                    BET Surface Area Report

     BET Surface Area:             157.9284  ±    6.7657 m²/g
     Slope:                          0.028212 ±   0.001159
     Y-Intercept:                   -0.000648 ±   0.000227
     C:                            -42.564236
     VM:                            36.278699    cm³/g STP
     Correlation Coefficient:        9.983172e-01

     Molecular Cross-section:        0.1620       nm²

  Relative                     Vol                        1/
  Pressure                   Adsorbed             [VA*(Po/P - 1)]
                            (cm³/g STP)

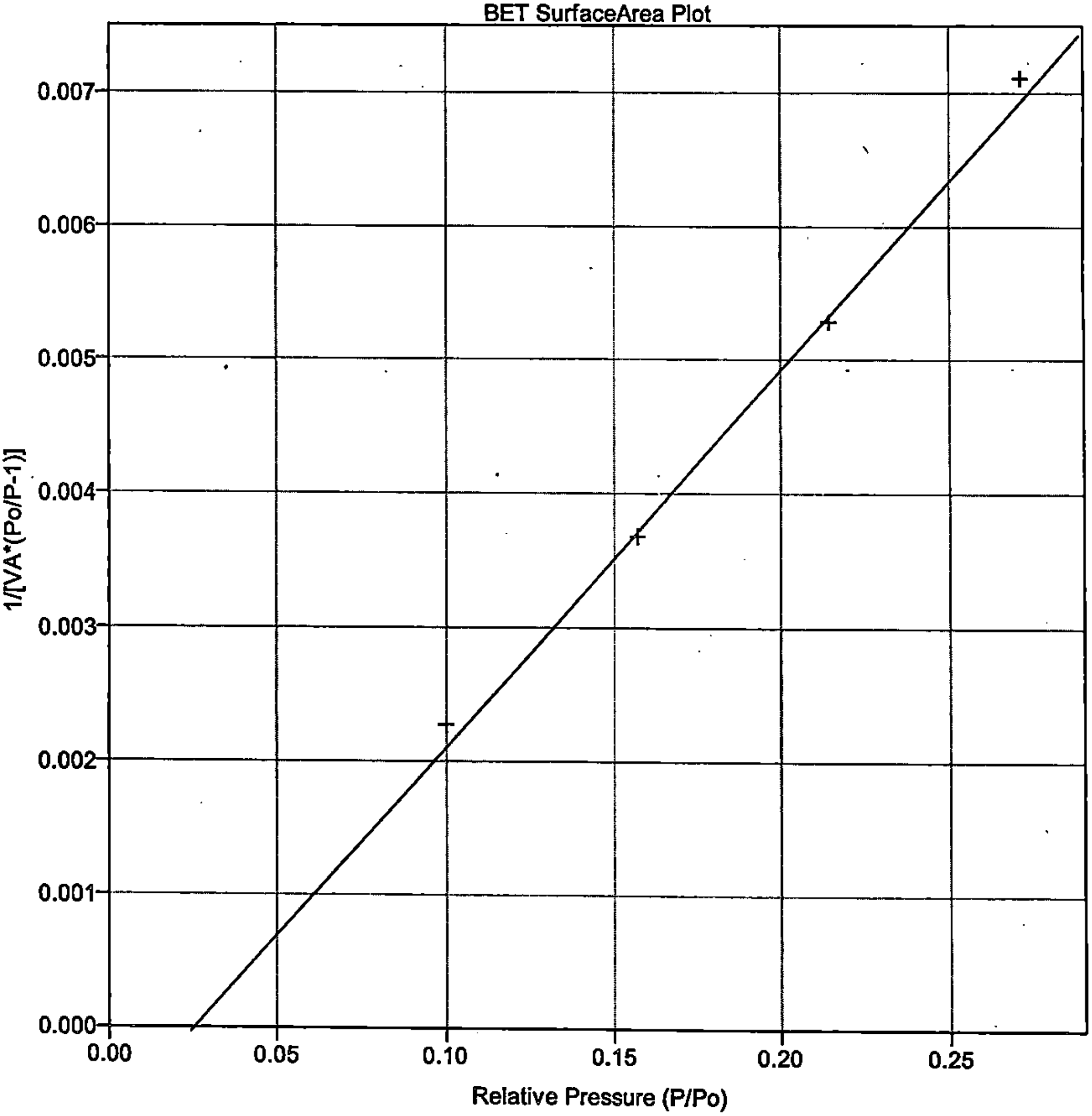
 0.099938120                 48.8041                     0.002275
 0.157042011                 50.5955                     0.003682
 0.214152223                 51.5563                     0.005286
 0.271199271                 52.3420                     0.007109
```

APPENDIX – II

Report on surface area analysis of tender coconut husk biochar

Sample ID: Biochar Mariya dainy

Started:	8/19/3813 3:55:21PM	Sat. Pressure:	791.89 mmHg
Completed:	8/19/3813 6:24:10PM	Freespace:	None
Report Time:	8/19/2013 6:17:53PM	Sample Weight:	0.1225 g
Evac. Rate:	300.0 mmHg/min	Evac. Time:	1.000000 minutes
Analysis Mode:	Equilibration	Equil. Interval:	3 secs



APPENDIX – II

Report on surface area analysis of tender coconut husk biochar

```
Sample ID: Biochar Mariya dainy


     Started: 8/19/3813 3:55:21PM          Sat. Pressure: 791.89 mmHg
   Completed: 8/19/3813 6:24:10PM              Freespace: None
 Report Time: 8/19/2013 6:17:53PM          Sample Weight: 0.1225 g
  Evac. Rate: 300.0 mmHg/min                  Evac. Time: 1.000000 minutes
Analysis Mode: Equilibration             Equil. Interval: 3 secs
```

```
                    Langmuir Surface Area Report

    Langmuir Surface Area:       237.8072   ±    1.0197 m²/g
    Slope:                         0.018306 ±    0.000078
    Y-Intercept:                   0.000224 ±    0.000015
    b:                             0.012262
    VM:                          54.628143     cm³/g STP
    Correlation Coefficient:     9.999816e-01

    Molecular Cross-section:     0.1620        nm²

 Relative                         Vol                          1/
 Pressure                       Adsorbed                 [VA*(Po/P)]
                               (cm³/g STP)

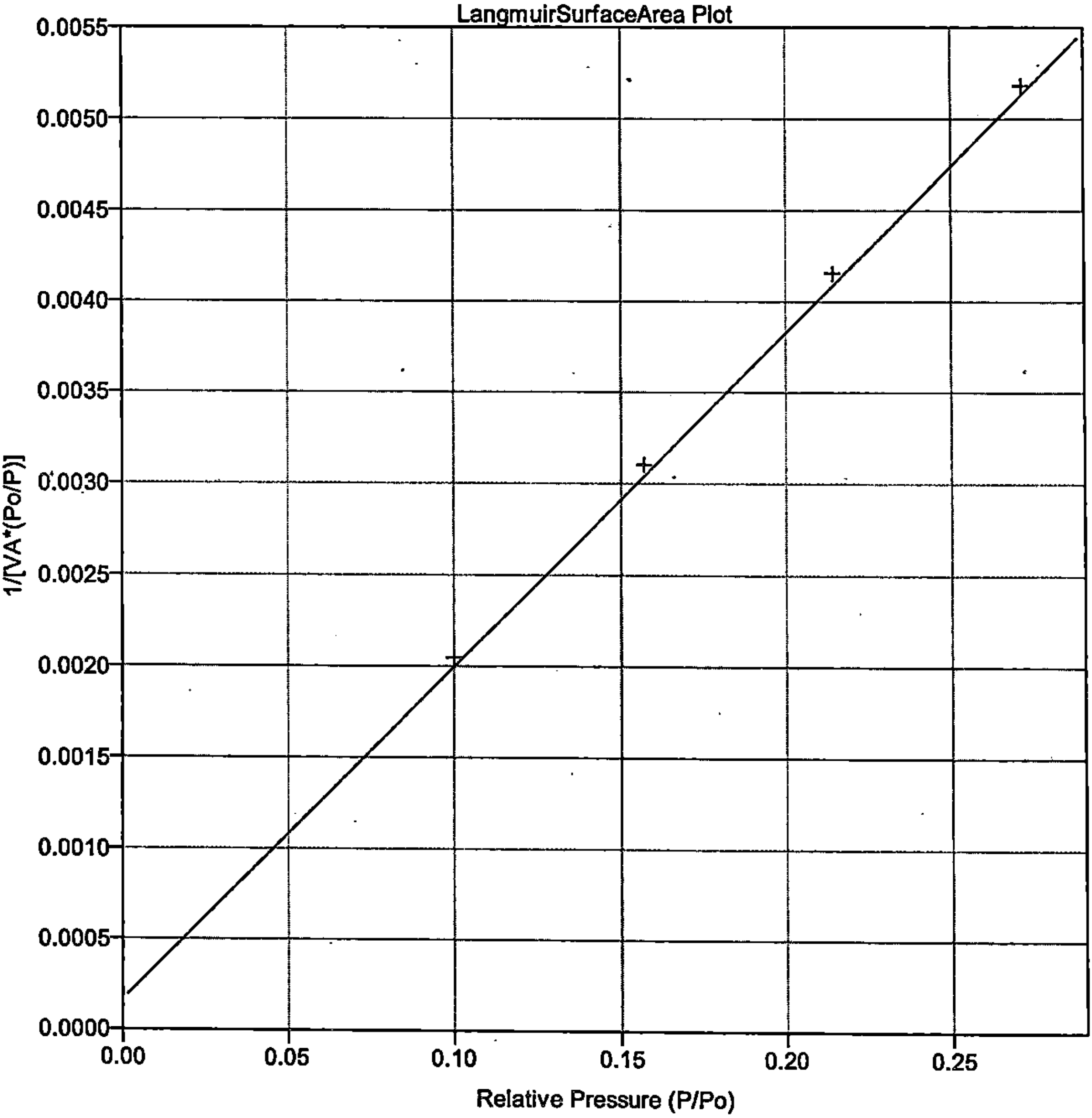
0.099938120                     48.8041                    0.002048
0.157042011                     50.5955                    0.003104
0.214152223                     51.5563                    0.004154
0.271199271                     52.3420                    0.005181
```

APPENDIX – II

Report on surface area analysis of tender coconut husk biochar

Sample ID: Biochar Mariya dainy

```
     Started: 8/19/3813 3:55:21PM          Sat. Pressure: 791.89 mmHg
   Completed: 8/19/3813 6:24:10PM              Freespace: None
 Report Time: 8/19/2013 6:17:53PM          Sample Weight: 0.1225 g
  Evac. Rate: 300.0 mmHg/min                  Evac. Time: 1.000000 minutes
Analysis Mode: Equilibration             Equil. Interval: 3 secs
```



APPENDIX – II

Report on surface area analysis of tender coconut husk biochar

```
  Sample ID: Biochar Mariya dainy


     Started: 8/19/3813 3:55:21PM          Sat. Pressure: 791.89 mmHg
   Completed: 8/19/3813 6:24:10PM              Freespace: None
 Report Time: 8/19/2013 6:17:53PM          Sample Weight: 0.1225 g
  Evac. Rate: 300.0 mmHg/min                  Evac. Time: 1.000000 minutes
Analysis Mode: Equilibration            Equil. Interval: 3 secs

                              t-Plot Report

           Micropore Volume:                   0.058538 cm³/g
           Micropore Area:                   110.8265   m²/g
           External Surface Area:             47.1019   m²/g
           Slope:                              3.045118  ±    0.378523
           Y-Intercept:                       37.844864  ±    1.621507
           Correlation Coefficient:            9.84897e-01
           Thickness Range:              3.5000 to   5.0000 A

             t = [13.9900 / (0.0340 - log(P/Po))] 0.5000

           Surface Area Correction Factor:  1.00
           Density Conversion Factor:       0.001547
           Total Surface Area (by  BET):  157.9284

   Relative                    Statistical                    Vol Adsorbed
   Pressure                   Thickness, (A)                     (cm³/g)

  0.099938120                     3.6778                          48.8041
  0.157042011                     4.0859                          50.5955
  0.214152223                     4.4601                          51.5563
  0.271199271                     4.8259                          52.3420
  0.328303181                     5.1983                          52.9527
  0.385407072                     5.5877                          53.3478
  0.442460441                     6.0038                          53.6845
  0.499690620                     6.4594                          54.0167
  0.556819753                     6.9662                          54.3669
  0.613967847                     7.5434                          54.6902
  0.671343236                     8.2199                          55.0314
```

APPENDIX – II

Report on surface area analysis of tender coconut husk biochar

Sample ID: Biochar Mariya dainy

```
     Started: 8/19/3813 3:55:21PM          Sat. Pressure: 791.89 mmHg
   Completed: 8/19/3813 6:24:10PM              Freespace: None
 Report Time: 8/19/2013 6:17:53PM          Sample Weight: 0.1225 g
  Evac. Rate: 300.0 mmHg/min                  Evac. Time: 1.000000 minutes
Analysis Mode: Equilibration             Equil. Interval: 3 secs
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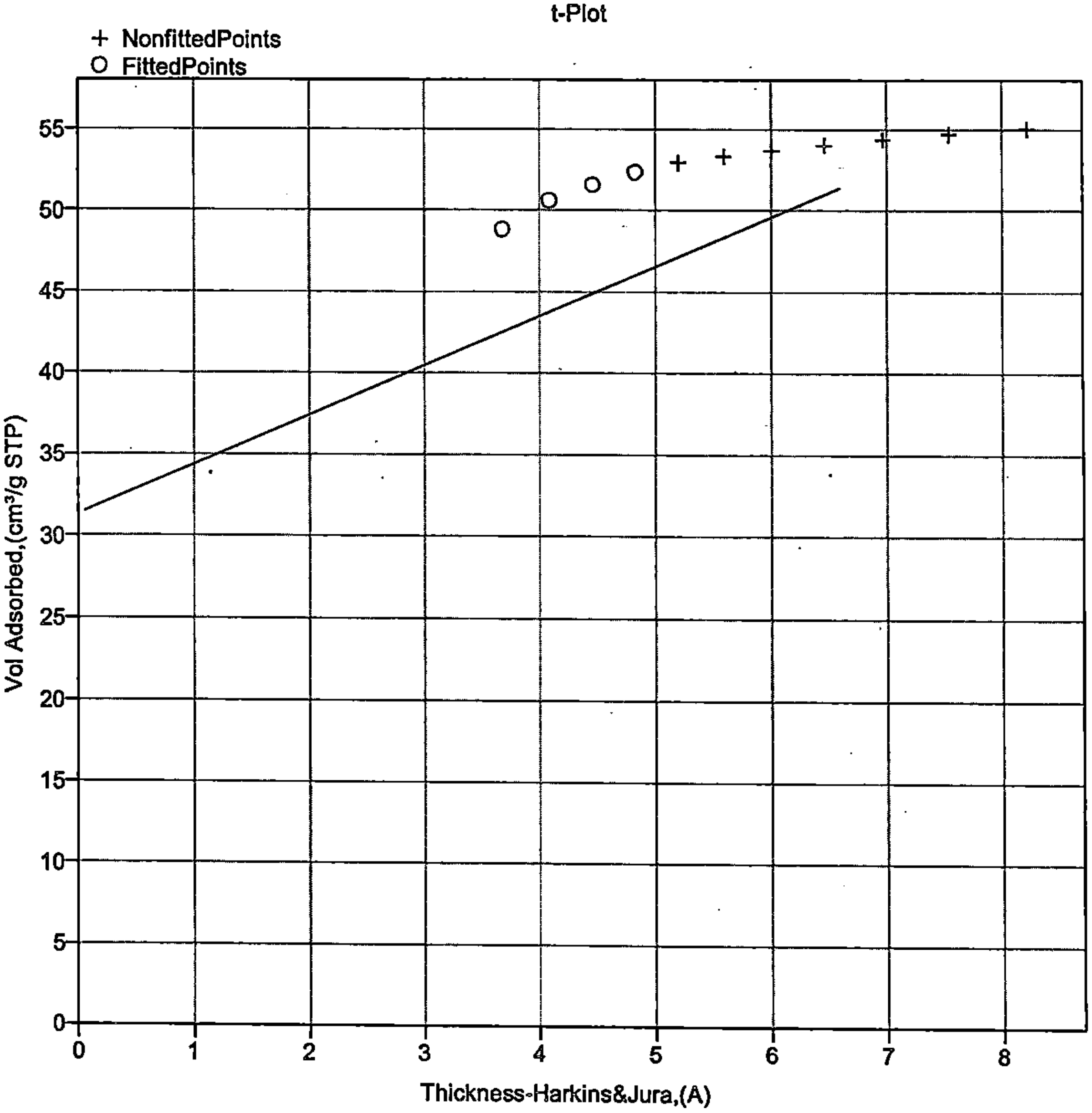


APPENDIX – II

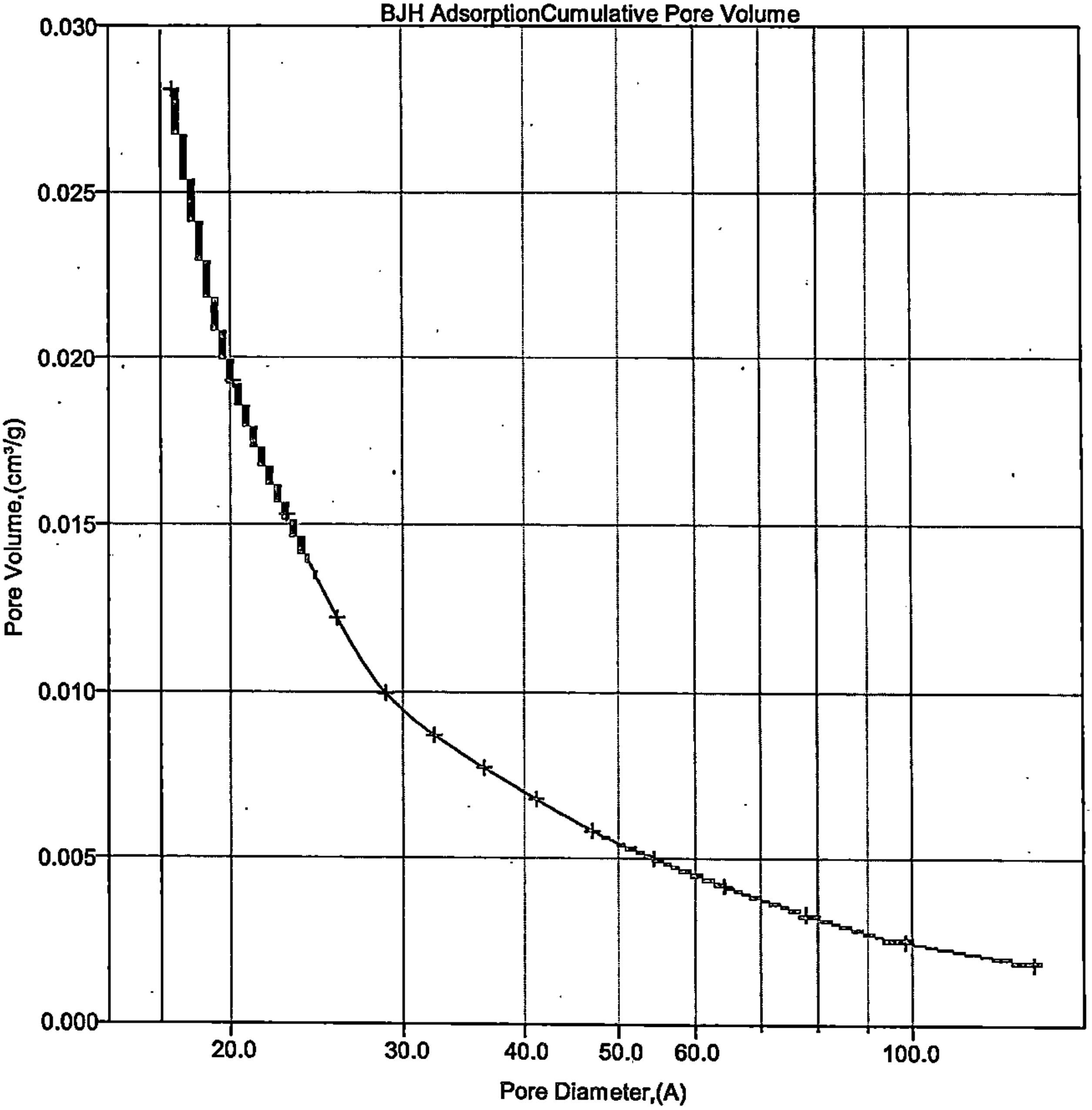
Report on surface area analysis of tender coconut husk biochar

```
Sample ID: Biochar Mariya dainy


      Started: 8/19/3813 3:55:21PM          Sat. Pressure: 791.89 mmHg
    Completed: 8/19/3813 6:24:10PM              Freespace: None
  Report Time: 8/19/2013 6:17:53PM          Sample Weight: 0.1225 g
   Evac. Rate: 300.0 mmHg/min                  Evac. Time: 1.000000 minutes
Analysis Mode: Equilibration              Equil. Interval: 3 secs
```

```
                  BJH Adsorption Pore Distribution Report

                  t = 3.5400 x [-5.0000 / ln(P/Po)]0.3330

                       Diameter Range: 17.0000 to 3000.0000 A
                       Adsorbate Property Factor: 9.530000 A
                       Density Conversion Factor: 0.001547
                       Fraction of Pores Open at Both Ends: 0.000

    Pore        Average     Incremental    Cumulative    Incremental    Cumulative
  Diameter      Diameter    Pore Volume    Pore Volume    Pore Area     Pore Area
 Range (A)        (A)         (cm³/g)        (cm³/g)        (m²/g)        (m²/g)

205.8- 133.3     153.5       0.001830       0.001830       0.477          0.477
133.3-  98.4     110.1       0.000655       0.002485       0.238          0.715
 98.4-  77.9      85.5       0.000835       0.003320       0.391          1.106
 77.9-  64.3      69.6       0.000836       0.004156       0.481          1.586
 64.3-  54.4      58.4       0.000842       0.004998       0.577          2.163
 54.4-  47.0      50.1       0.000830       0.005829       0.663          2.827
 47.0-  41.1      43.6       0.000958       0.006787       0.879          3.706
 41.1-  36.3      38.4       0.000934       0.007721       0.974          4.680
 36.3-  32.3      34.0       0.000988       0.008709       1.162          5.842
 32.3-  28.8      30.3       0.001257       0.009966       1.661          7.503
 28.8-  25.7      27.0       0.002240       0.012205       3.318         10.821
 25.7-  22.8      24.0       0.003105       0.015310       5.167         15.988
 22.8-  20.2      21.3       0.004002       0.019312       7.528         23.516
 20.2-  17.4      18.5       0.008793       0.028105      18.994         42.510
```

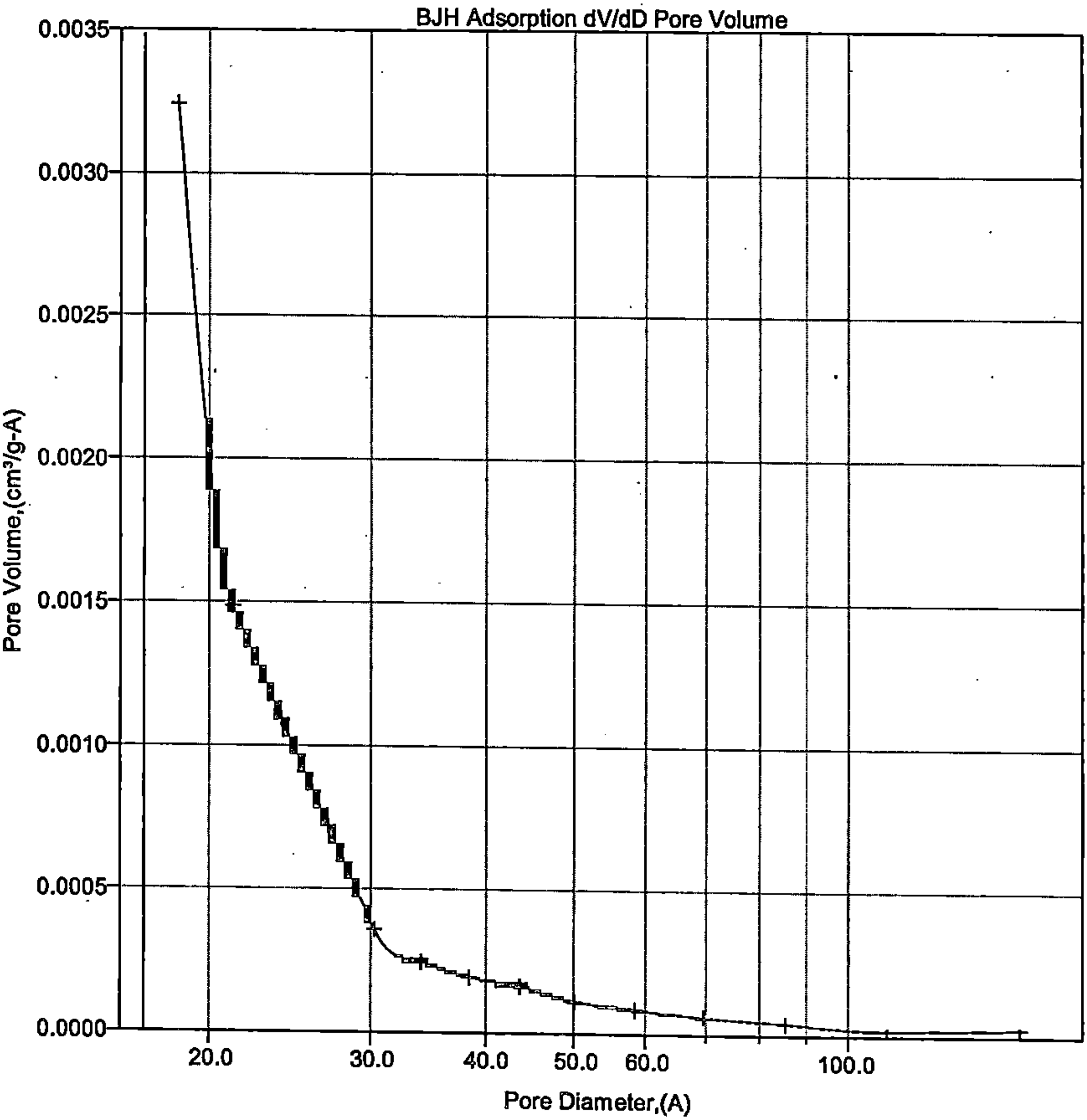
Sample ID: Biochar Mariya dainy

```
      Started: 8/19/3813 3:55:21PM        Sat. Pressure: 791.89 mmHg
    Completed: 8/19/3813 6:24:10PM            Freespace: None
  Report Time: 8/19/2013 6:17:53PM        Sample Weight: 0.1225 g
   Evac. Rate: 300.0 mmHg/min                Evac. Time: 1.000000 minutes
Analysis Mode: Equilibration           Equil. Interval: 3 secs
```



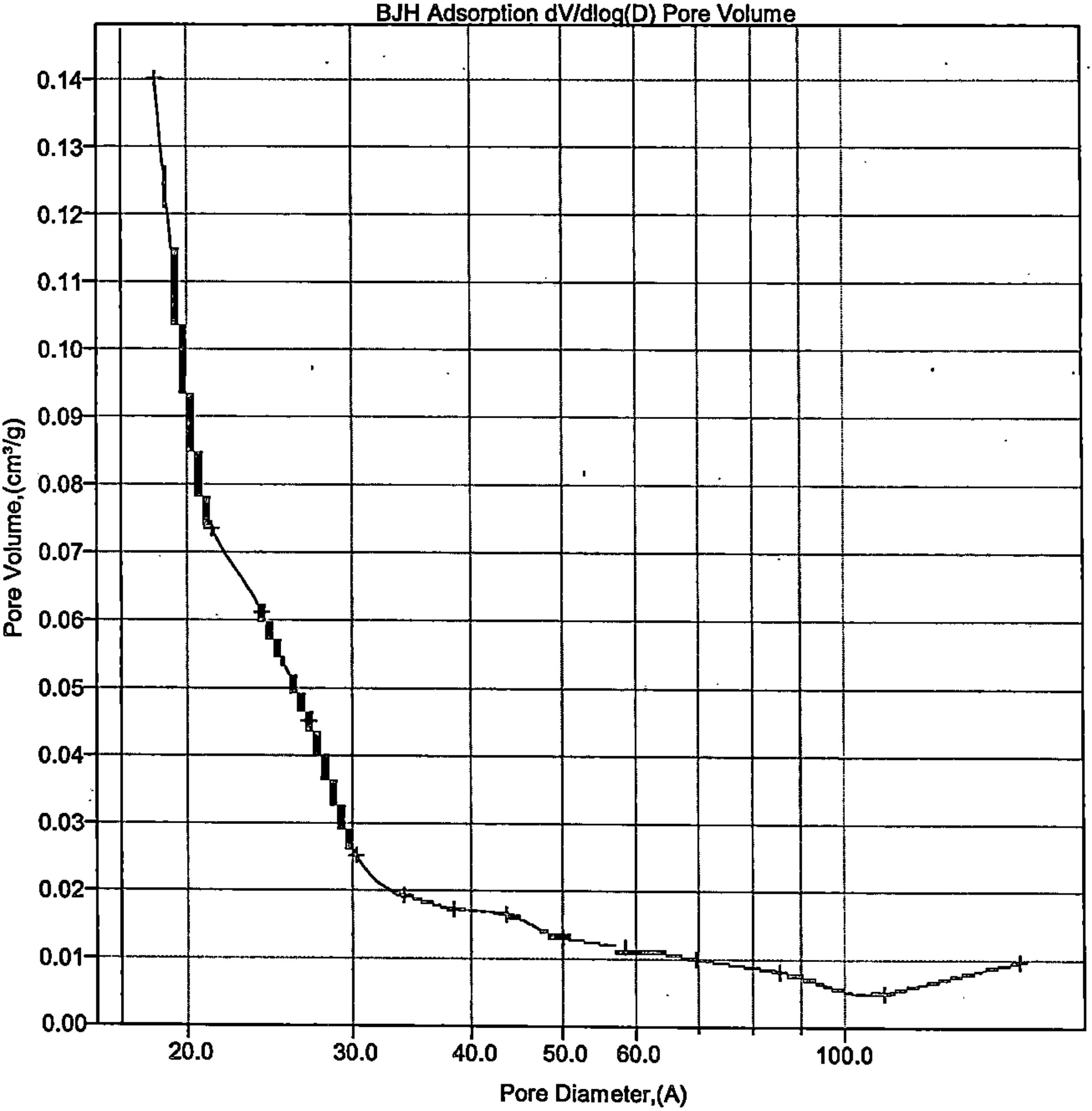
Sample ID: Biochar Mariya dainy

```
    Started: 8/19/3813 3:55:21PM        Sat. Pressure: 791.89 mmHg
  Completed: 8/19/3813 6:24:10PM            Freespace: None
Report Time: 8/19/2013 6:17:53PM        Sample Weight: 0.1225 g
 Evac. Rate: 300.0 mmHg/min                Evac. Time: 1.000000 minutes
Analysis Mode: Equilibration          Equil. Interval: 3 secs
```



Sample ID: Biochar Mariya dainy

```
      Started: 8/19/3813 3:55:21PM        Sat. Pressure: 791.89 mmHg
    Completed: 8/19/3813 6:24:10PM            Freespace: None
  Report Time: 8/19/2013 6:17:53PM        Sample Weight: 0.1225 g
   Evac. Rate: 300.0 mmHg/min                Evac. Time: 1.000000 minutes
Analysis Mode: Equilibration            Equil. Interval: 3 secs
```



```
    Sample ID: Biochar Mariya dainy


      Started: 8/19/3813 3:55:21PM        Sat. Pressure: 791.89 mmHg
    Completed: 8/19/3813 6:24:10PM            Freespace: None
  Report Time: 8/19/2013 6:17:53PM        Sample Weight: 0.1225 g
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Analysis Mode: Equilibration            Equil. Interval: 3 secs
```

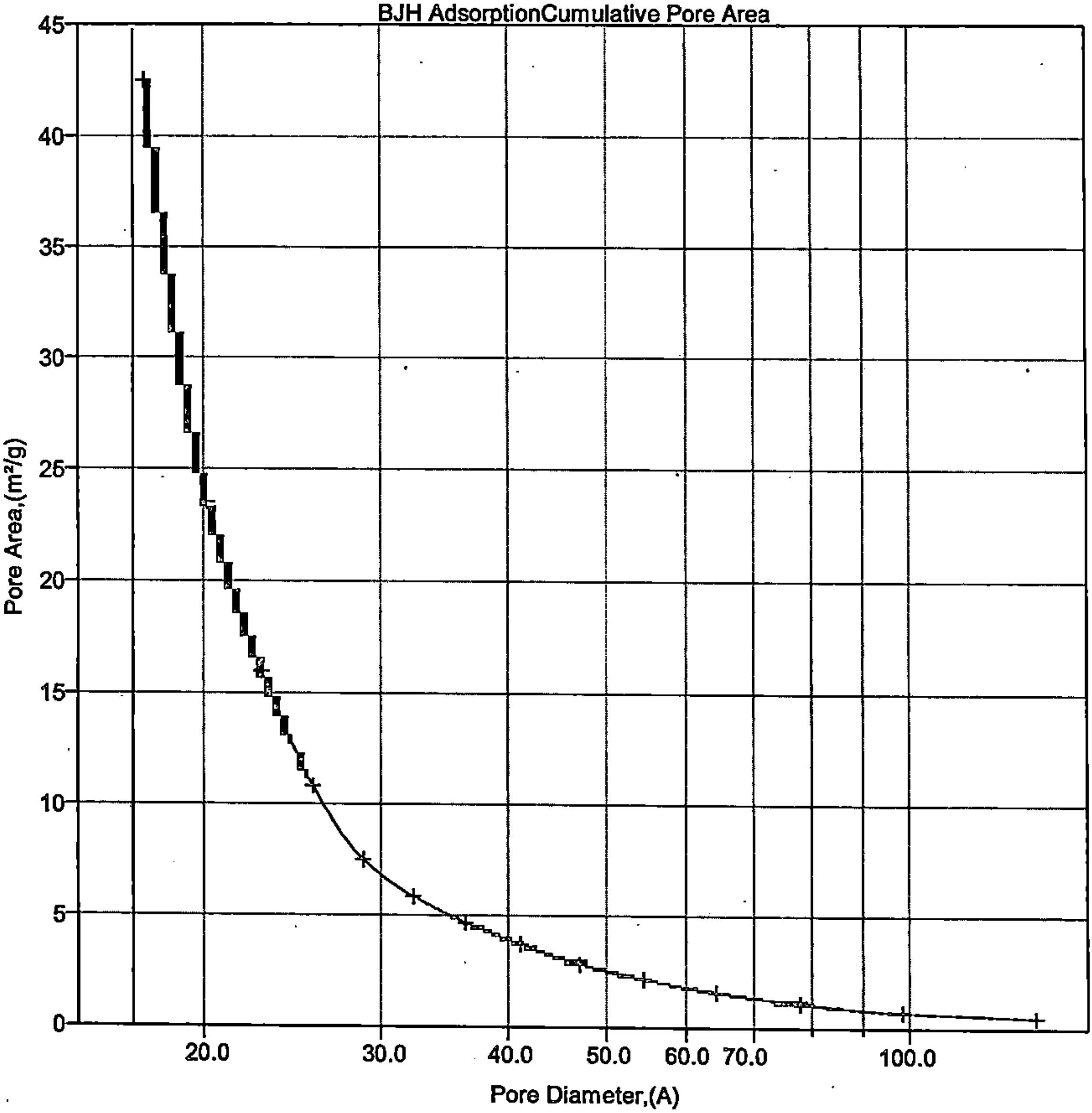

Sample ID: Biochar Mariya dainy

```
     Started: 8/19/3813 3:55:21PM        Sat. Pressure: 791.89 mmHg
   Completed: 8/19/3813 6:24:10PM            Freespace: None
 Report Time: 8/19/2013 6:17:53PM        Sample Weight: 0.1225 g
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Analysis Mode: Equilibration            Equil. Interval: 3 secs
```

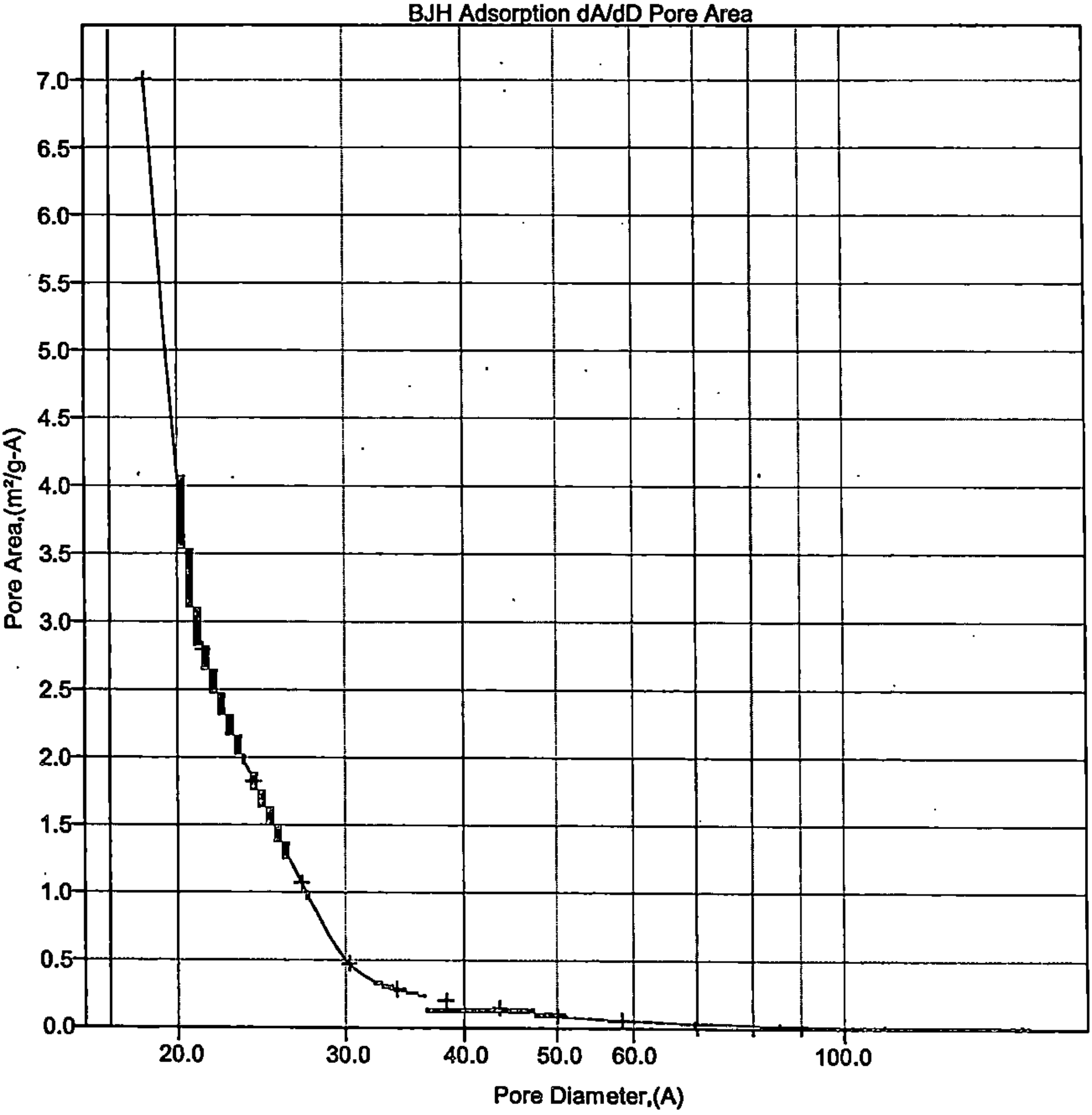

Sample ID: Biochar Mariya dainy

```
     Started: 8/19/3813 3:55:21PM        Sat. Pressure: 791.89 mmHg
   Completed: 8/19/3813 6:24:10PM            Freespace: None
 Report Time: 8/19/2013 6:17:53PM        Sample Weight: 0.1225 g
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Analysis Mode: Equilibration           Equil. Interval: 3 secs
```

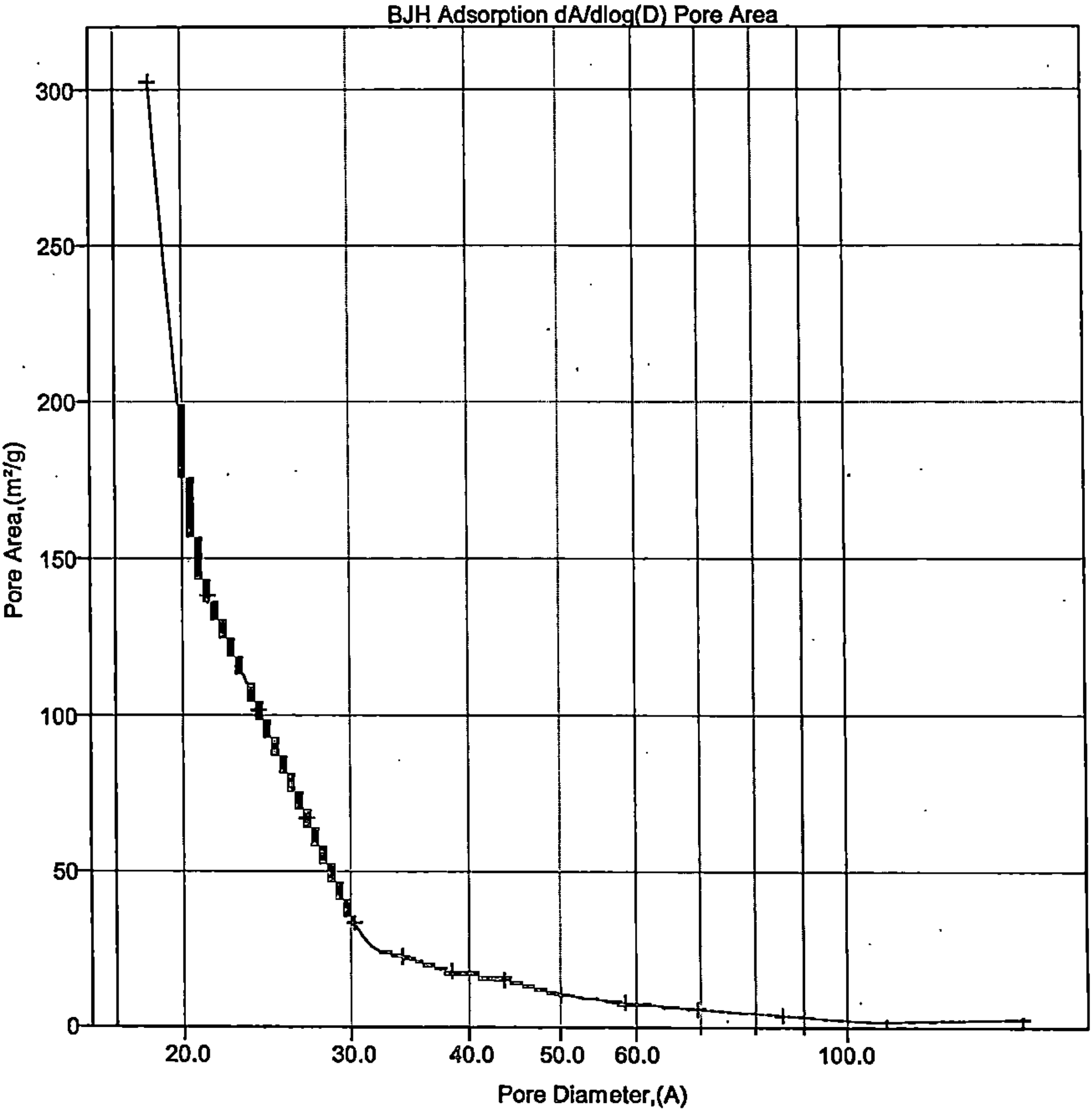

```
     Sample ID: Biochar Mariya dainy


        Started: 8/19/3813 3:55:21PM          Sat. Pressure: 791.89 mmHg
      Completed: 8/19/3813 6:24:10PM              Freespace: None
    Report Time: 8/19/2013 6:17:53PM          Sample Weight: 0.1225 g
     Evac. Rate: 300.0 mmHg/min                  Evac. Time: 1.000000 minutes
  Analysis Mode: Equilibration              Equil. Interval: 3 secs
               ____________________________________________________

                                  Summary Report

                                       Area


Single Point Surface Area at P/Po 0.27119927 :                   166.0611   m²/g

BET Surface Area:                                                157.9284   m²/g

Langmuir Surface Area:                                           237.8072   m²/g

Micropore Area:                                                  110.8265   m²/g

External Surface Area:                                            47.1019   m²/g

BJH Adsorption Cumulative Surface Area of pores
    between 17.000000 and 3000.000000 A Diameter:                 42.5095   m²/g

                                      Volume


Micropore Volume:                                                0.058538 cm³/g

BJH Adsorption Cumulative Pore Volume of pores
    between 17.000000 and 3000.000000 A Diameter:                0.028105 cm³/g

                                    Pore Size


BJH Adsorption Average Pore Diameter (4V/A):                      26.4455   A
```