TECHNOLOGY REFINEMENT FOR BIOCHAR PRODUCTION AND EVALUATION OF ITS EFFECT ON SOIL HEALTH AND CROP PRODUCTIVITY

by

SAINATH NAGULA

(2014-21-134)

THESIS

Submitted in partial fulfilment 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

VELLAYANI, THIRUVANANTHAPURAM - 695 522

KERALA, INDIA

2017

DECLARATION

I, hereby declare that this thesis entitled **"TECHNOLOGY REFINEMENT FOR BIOCHAR PRODUCTION AND EVALUATION OF ITS EFFECT ON SOIL HEALTH AND CROP PRODUCTIVITY"** is a bonafide record of research work done by me during the course of research and the thesis has not previously formed the basis for the award to me of any degree, diploma, associateship, fellowship or other similar title, of any other University or Society.

Vellayani
Date: 26-08-2017

Sainath Nagula
(2014-21-134)

CERTIFICATE

Certified that this thesis entitled **"TECHNOLOGY REFINEMENT FOR BIOCHAR PRODUCTION AND EVALUATION OF ITS EFFECT ON SOIL HEALTH AND CROP PRODUCTIVITY"** is a record of research work done independently by Mr. Sainath Nagula under my guidance and supervision and that it has not previously formed the basis for the award of any degree, diploma, fellowship or associateship to him.

Vellayani
Date: 26-08-2017

Dr. P.B. Usha
(Major Advisor, Advisory Committee)
Professor
(Soil Science and Agricultural Chemistry)
College of Agriculture
Vellayani

CERTIFICATE

We, the undersigned members of the advisory committee of Mr. Sainath Nagula, a candidate for the degree of **Doctor of Philosophy in Agriculture** with major in Soil Science and Agricultural Chemistry, agree that the thesis entitled **"TECHNOLOGY REFINEMENT FOR BIOCHAR PRODUCTION AND EVALUATION OF ITS EFFECT ON SOIL HEALTH AND CROP PRODUCTIVITY"** may be submitted by Mr. Sainath Nagula, in partial fulfilment of the requirement for the degree.

26/8/17
Dr. P.B Usha
(Chairman, Advisory Committee)
Professor
Department of Soil Science and
Agricultural Chemistry
College of Agriculture, Vellayani

26/8/17
Dr. Sam T. Kurumthottical
(Member, Advisory Committee)
Professor and Head
Department of Soil Science and
Agricultural Chemistry
College of Agriculture, Vellayani

K.C. Manorama
26/8/17
Dr. K. C. Manorama Thampatti
(Member, Advisory Committee)
Professor
Department of Soil Science and
Agricultural Chemistry
College of Agriculture, Vellayani

26/8/17
Dr. Biju Joseph
(Member, Advisory Committee)
Assistant Professor
Instructional Farm,
College of Agriculture, Vellayani

26/08/2017
Dr. D. Dhalin
(Member, Advisory Committee)
Assistant Professor
Department of Agricultural Engineering
College of Agriculture, Vellayani

26/8/2017.
EXTERNAL EXAMINER
(V. RAMESH)
PRINCIPAL SCIENTIST
ICAR-CTCRI
THIRUVANANTHAPURAM

ACKNOWLEDGEMENTS

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.

It is indeed with immense joy that I wish to place on record my profound gratitude, obligation and admiration to ***Dr. P. B. Usha****, Professor, Soil Science and Agricultural Chemistry and Chairman of the Advisory Committee who has been a guide and mentor to me. Her enthusiastic scientific zeal and remarkable research acumen served to instill confidence and fortitude in me, which have gone a long way in accomplishing this arduous task diligently.*

I respectfully thank ***Dr. Sam T Kurumthottical****, Professor and Head, Department of Soil Science and Agricultural Chemistry and member of my Advisory Committee for bestowing constant support, care and encouragement on me.*

I am deeply obliged to ***Dr. K. C. Manorama Thampatti****, Professor, Soil Science and Agricultural Chemistry and member of the Advisory Committee for her outright categorical, critical comments and wise, apt, infallible pieces of advice.*

My sincere thanks are due to ***Dr. Biju Joseph****, Assistant Professor, Instructional Farm and member of the Advisory Committee who had been instrumental in guiding me through the field experiment.*

Dr. D. Dhalin*, Assistant Professor, Department of Agricultural Engineering and member of the Advisory Committee is of unpretentious nature and forthcoming in advice, for which I am grateful to him.*

I wish to express my sincere thanks to ***Dr. N. Saifudeen****,* ***Dr. Sumam Susan Varghese*** *and* ***Dr. Sumam George****, Former Professors and Head of Department of Soil Science and Agricultural Chemistry for their technical interventions and inspiring attitude in formulating the technical programme and helping me in executing it.*

I gratefully acknowledge the invaluable suggestions and unstinting support of the other esteemed faculty members of the Department of Soil Science and Agricultural Chemistry ***Dr. C R Sudharmaidevi, Dr. Usha Mathew, Dr. K Ushakumari, Dr. B Rani, Dr. B. Aparna, Dr. R. Gladis, Dr. Thomas George and Dr. Naveen Leno.***

5

I thank my colleagues Sreya, Pritin, Sreekanth, Pinturoy, Sreelakshmi, Bibishan, Darshan, Vinay, Siddesh and Ravikishore; Ph.D. Scholars Fazila E K, Meera A V, Priya U K, Visweswaran S, Rekha V and Nibin P M; Dhanya, Dhaneesh, Rakhi, Anjana, Usharani and other P.G. Scholars for their honest assistance.

Services of the non-teaching and supporting staff of the department Maya chechi, Biju chettan, Aneesh, Soumya chechi, Shiny chechi and Geethu chichi who have helped me earnestly are gratefully acknowledged.

I wish to acknowledge with gratitude the award of National fellowship for OBC by the University Grants Commission during the tenure of the Ph. D. (Ag.) programme.

I am most indebted to my loving father Mr. Bhoomanna, mother Mrs. Laxmi, sister Sujatha, brother Dathatri, 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 completed this research.

In all humility I thank one and all who have directly or indirectly been of help to me in achieving this goal.

Sainath Nagula

CONTENTS

Chapter No.	Title	Page No.
1	INTRODUCTION	1-3
2	REVIEW OF LITERATURE	4-28
3	MATERIALS AND METHODS	29-41
4	RESULTS	42-95
5	DISCUSSION	96-127
6	SUMMARY	128-132
7	REFERENCES	133-155
	ABSTRACT	156-158
	APPENDICES	159-161

LIST OF TABLES

Table No.	Title	Page No.
1	Standard analytical methods for characterization of biochar	30
2	Analytical procedures followed for soil analysis in the experimental field	32
3	Treatment combinations of field experiment	34
4	Analytical methods of foliar nutrient analysis	36
5	Temperature build up within the reactor unit of the micro biochar kiln	54
6	Specifications of the indigenously designed and fabricated micro biochar kiln	54
7	Electro-chemical and chemical characteristics of biochar from tender coconut husk	55
8	Heavy metal content in biochar from tender coconut husk	55
9	Composition of syngas produced during pyrolysis of tender coconut husk	56
10	Soil fertility parameters of experimental site	58
11	Fertilizer requirement for different treatments for banana	59
12	Effect of treatments on plant height of banana, cm	62
13	Effect of treatments on pseudostem girth of banana, cm	62
14	Effect of treatments on number of leaves of banana	63
15	Effect of treatments on dry matter production in banana, kg ha^{-1}	63
16	Effect of treatments on bunch yield and bunch characters of banana	64
17	Effect of treatments on quality parameters of fruit of banana	64
18	Incidence of pests and disease (%) in the field experiment	69
19	Effect of treatments on soil physical properties	73

Table No.	Title	Page No.
20	Effect of treatments on soil electro-chemical and chemical properties	73
21	Effect of treatments on soil available N at different growth stages, kg ha^{-1}	77
22	Effect of treatments on soil available P at different growth stages, kg ha^{-1}	77
23	Effect of treatments on soil available K at different growth stages, kg ha^{-1}	78
24	Effect of treatments on soil available Ca at different growth stages, mg kg^{-1}	78
25	Effect of treatments on soil available Mg at different growth stages, mg kg^{-1}	82
26	Effect of treatments on soil available S at different growth stages, mg kg^{-1}	82
27	Effect of treatments on soil available Zn at different growth stages, mg kg^{-1}	83
28	Effect of treatments soil on available Cu at different growth stages, mg kg^{-1}	83
29	Effect of treatments on soil available B at different growth stages, mg kg^{-1}	84
30	Effect of treatments on soil dehydrogenase activity, µg TPF g^{-1} soil 24 h^{-1}	84
31	Effect of biochar based treatments on foliar N, P and K concentration, %	87
32	Effect of biochar based treatments on foliar Ca, Mg and S concentration, %	87
33	Effect of biochar based treatments on foliar Fe, Mn and Zn concentration, mg kg^{-1}	89
34	Effect of biochar based treatments on foliar Cu and B concentration, mg kg^{-1}	89
35	Effect of treatments on nutrient use efficiency (NUE), %	91
36	Correlation of yield with soil physical, chemical and biological parameters	93
37	Correlation of growth characters with yield and yield attributes	94
38	Cost of biochar production	95

Table No.	Title	Page No.
39	Effect of treatments on gross income, net returns and B:C ratio of the treatments	95
40	Comparison between control and the best treatment	127

LIST OF FIGURES

Figure No.	Title	Page No.
1	Weather parameters during the growth period of banana crop	39
2	Lay out of experiment field	40
3	Temperature build up within the reactor unit of the micro biochar kiln	103
4	Waterloo-mechanism of primary decomposition of cellulose	103
5	Fertility indices of biochar in terms of C:N, C:P and C:S ratios. Error bars indicate standard deviation from the mean (n =3)	104
6	Syngas composition during pyrolysis of tender coconut husk	104
7	Effect of treatments on soil water holding capacity at harvest stage	107
8	Effect of treatments on soil bulk density at harvest stage	107
9	Effect of treatments on soil pH at harvest stage	108
10	Effect of treatments on soil cation exchange capacity at harvest stage	108
11	Effect of treatments on soil available N at different stages	111
12	Effect of treatments on soil available P at different stages	111
13	Effect of treatments on soil available K at different stages	112
14	Effect of treatments on soil available Ca at different stages	112
15	Effect of treatments on soil available Mg at different stages	119
16	Effect of treatments on soil available S at different stages	119
17	Effect of treatments on soil available Zn at different stages	120
18	Effect of treatments on soil available Cu at different stages	120
19	Effect of treatments on soil available B at different stages	121
20	Effect of treatments on soil dehydrogenase activity at harvest stage	121

LIST OF PLATES

Plate No.	Title	Page No.
1	A view of the experiment field	38
2	Imagery of the location of the experiment site	41
3	Previous model biochar kiln (Dainy. 2015)	46
4	Modified micro biochar kiln	46
5	Outer barrel of the double barrel reactor unit of the prototype micro biochar kiln	45
6	Inner biomass barrel of the double barrel reactor unit of the prototype micro biochar kiln	46
7	Cooling assembly for condensation, saturation and collection of syngas, byproduct of pyrolysis	47
8	Parts of the indigenously designed and fabricated prototype of micro kiln	48
9	Schematic diagram showing placement of smaller biomass barrel inside the larger fuel barrel	49
10	Steps in pyrolytic production of biochar in the micro kiln	50
11	A view of biochar production from tender coconut husk	51
12	Bunch yield of banana in different treatments	65
13	Biochar based different treatments effect on Index fruit of banana	67
14	Biochar based different treatments effect on shelf life of banana	68
15	Biochar based nutrient mix for nendran banana	92

LIST OF APPENDICES

Sl. No.	Title	Appendix No.	Page No.
1	Weather parameters during the cropping period (September 2015 to June 2016)	I	159
2	Effect of treatments on total cost, gross income and net returns	II	159
3	Composition of syngas analyzed using micro gas chromatograph	III A	160
4	Composition of syngas analyzed using micro gas chromatograph	III B	161

LIST OF ABBREVIATIONS

%	Per cent
@	At the rate of
°C	Degree Celsius
AEC	Anion Exchange Capacity
B	Boron
BC	Biochar
B:C	Benefit : Cost
BD	Bulk density
C	Carbon
CD	Critical difference
C:N	Carbon : Nitrogen
C:P	Carbon : Phosphorus
C:S	Carbon : Sulphur
CEC	Cation Exchange Capacity
Ca	Calcium
Cd	Cadmium
Cr	Chromium
Cu	Copper
dS	Deci Siemen
EC	Electrical conductivity
et al.	And others
Fe	Iron
FYM	Farm yard manure
g	Gram
g kg^{-1}	Gram per kilogram

GHG	Greenhouse gas
HS	Harvest stage
K	Potassium
m	Meter
MAP	Months after planting
Mg	Magnesium
mg kg^{-1}	Milligram per kilogram
Mn	Manganese
N	Nitrogen
Ni	Nickel
NUE	Nutrient use efficiency
OC	Organic carbon
P	Phosphorus
PM	Particulate matter
Pb	Lead
POP	Package of Practices
RBD	Randomised block design
S	Sulphur
SOC	Soil organic carbon
STBR	Soil test based recommendations
t ha^{-1}	Tons per hectare
TOC	Total organic carbon
TSS	Total soluble solids
WHC	Water holding capacity
Zn	Zinc

INTRODUCTION

1. INTRODUCTION

Biochar can be produced by the thermochemical degradation of biomass in a zero or limited oxygen environment through the process of pyrolysis. It is perhaps the most recalcitrant form of organic matter in soil, whose sustenance extends from a few hundreds to thousands of years, rendering it an excellent means for carbon sequestration. Owing to its aromatic structure dominated by aromatic carbon, biochar has been found to be biochemically recalcitrant as comparison with the uncharred, original organic matter of genesis and is seemingly prospective in supplementing the long term soil carbon pool, with a net carbon withdrawal from the atmosphere of 20 percent. Biochar application can reduce emission of other greenhouse gases like nitrous oxide by 80 percent and completely suppresses methane emissions from soil.

Biochar has prime significance in enhancing soil fertility and it can probably play a role as a soil amendment leading to improved plant growth and crop yield. The most unique characteristic of biochar is its effectiveness and efficiency in retaining most nutrients and keeping them available to plants as compared to conventional organic matter sources such as farm yard manure, green leaf manure or composts. The porous nature of biochar imparts an enhanced surface area which in turn facilitates the holding of water and nutrients and supply to plants and at the same time, keeps carbon intact without being emitted into the atmosphere. The chemical constitution of biochar comprising of polycondensed aromatic groups enables prolonged biochemical stability that helps to sustain the resistance to biotic decomposition. The partial oxidation also facilitates the highest retention of nutrients. Biochar application results in improved water holding capacity, increased pH, cation exchange capacity, biological nitrogen fixation and reduced leaching loss of nutrients. Biochar could adsorb ammonium ion predominantly by cation exchange and thus can be used as a nitrification inhibitor. Thus the use of biochar makes it possible to effect a paradigm shift in organic farming practices, to turn the balance sheet of carbon from a net emitter to a means of drawing carbon back out of the atmosphere. Moreover, biochar can effectively adsorb heavy metals such as lead and organics that contaminate soils. Hence the potential use of biochar as a bioremediator needs no over emphasis.

Agricultural residues, municipal yard waste and animal manure can be a menace to the environment. The enriched content of nutrient manure may cause either eutrophication of surface waters or pollute ground water. Landfills of municipal green waste may generate enormous amounts of greenhouse gases which would ultimately contribute to global warming and consequently lead to climate change. Biochar production is an intelligent and strategic method of recycling organic waste, reducing environmental pollution and mitigation of global climate change.

Globally India ranks third in coconut production with 14.91 million tons. Of this, 15 percent is consumed as tender coconuts. Sale of tender coconut nuts along waysides and parlours located by the side of highways and city roads has gained much popularity. Of late, it has been reported that there has been a 130 % increase in the sale of tender coconuts in Kerala, which is the largest producer with 600 crore nuts. The spent tender coconut husks which form a bio-waste are discarded along waysides. Accumulating heaps of discarded spent tender coconut husks have become a common sight in waysides of cities. The tender coconut husk is rich in lignocellulose and resistant to biotic degradation by the soil microorganisms. Combustion of this bio-waste is not an advisable proposition owing to the emanation of greenhouse gases which will lead to further of global warming. Hence the most viable technological option available at present is the environmentally safe disposal of the tender coconut husk waste biomass to biochar. During biochar production syngas and bio oil are generated as co-products that can be used as bioenergy source. Syngas can be utilized as cooking gas and as an alternate fuel for diesel engine. The prospective potential to have a harmonious blend encompassing bioenergy production, promotion of sustainable agriculture and a viable waste management strategy with a simultaneous reduction of greenhouse gas emissions favouring mitigation of global warming into a feasible approach using biochar synthesis offers the best way to handle bio-waste in a long term perspective of a future economy.

Several modern reactor configurations for pyrolytic synthesis of biomass substrates are in vogue in the industrial level. These comprise of the fixed bed, fluidized bed, heated kiln, rotating cone, ablative, screw feeder/auger and vacuum pyrolisers. However a developing low scale, cost effective, micro level kiln reactor suited for the pyrolytic synthesis of used tender coconut husk waste biomass, which helps in catering to disposal of these waste at source, is the need of the hour. Dainy (2015) indigenously developed a basic prototype of a biochar kiln for the pyrolytic production of biochar from tender coconut husk biomass. A refinement of this technology to increase the efficiency as well as quality of biochar production and its utilization for improving soil health and crop productivity need to be addressed. Hence this study was proposed with the following objectives.

1. Refinement of technology for micro level biochar production from tender coconut husk.
2. Characterization of the biochar and syngas analysis.
3. Evaluation of biochar application on soil health, yield and quality of banana (*Musa* spp.).

REVIEW OF LITERATURE

2. REVIEW OF LITERATURE

A study entitled 'Technology refinement for biochar production and evaluation of its effect on soil health and crop productivity' was undertaken at the College of Agriculture, Vellayani from March 2015 to June 2016 with the objectives of refinement of technology for micro level biochar production from tender coconut husk and evaluation of its effect on soil health, yield and quality of banana (*Musa* spp.).

The fourth largest global energy source and the first energy source in the developing countries representing 14 % to 35 % of primary energy is the biomass (Hall *et al*., 1992). The worldwide annual primary production of biomass is 220 billion oven dry tons (Hall and Rosillo-Calle, 1998) and the annual agricultural, forest biomass waste production in India is nearly 370 million tons (Pappu *et al.,* 2007). While considering the various sources of available lignocellulosic biomass on a global basis, a preponderance of agricultural wastes such as corn stover, wheat straw and rice straw can be observed (Loow *et al*., 2015). Biomass can be considered a good substrate for the synthesis of biochar, which would in turn be an answer to the vexing problem of waste management. The enormity and ease in which agricultural byproducts can be procured render them suitable substrates for biochar production, thereby acts as excellent sources for waste management (Sugumaran and Seshadri, 2009).

Biochar is a fine grained, black, solid, carbon rich (70-80 %) porous substance produced from thermochemical decomposition of biomass waste (e.g. wood waste, agricultural biomass waste and manure) in a near zero oxygen environment at relatively high temperature (> 350 °C) (Lehmann *et al.,* 2002; Thompson *et al.,* 2016). Biochar can be used for the immobilization of contaminants in water, soils and sediments (Thompson *et al.,* 2016), as well as for the improving crop productivity in weathered and eroded soils (Steiner *et al.,* 2007). Biochar with an inherent capability is an invaluable means for the agricultural industry with its unique ability to enhance soil health, improve the soil physical properties, soil pH, organic carbon content and carbon sequestration, prevent water loss and reduce drought, mitigate emission of greenhouse gases, conserve nutrients, decrease fertilizer additions, enhance crop productivity and is a preferential habitat for rhizospheric microorganisms.

2.1 BIOCHAR PRODUCTION

Biochar production technologies in vogue are designed and optimized for synthesis of biochar ahead of liquid tars and pyrotic gases. Though there are two common approaches that are prevalent which include slow and fast pyrolysis, the most successful process for better production of biochar production is through slow pyrolysis. A realisable yield between 25-35 % can be obtained under slow pyrolysis. The residence time of the feedstock is longer and the temperatures are lower than 700 °C in slow pyrolysis which would permit the remission of all volatile constituents, leaving behind a solid biochar. On an average, a 35 % yield of biochar is realisable through the process of slow pyrolysis. Moreover, this yield would depend on several other factors such as nature of the feedstock, type of reactor kiln as well as the optimization of the level of operating and process conditions etc. Reed and Das (1998) concluded that pyrolytic gasification is an example of heating through indirect means making use of an external container to burn a part of the fuel and utilising the heat energy thus produced to pyrolyze the feed stock producing medium energy gas with significant fraction of tars. There are great prospects for modification in such a design to produce biochar because the movement of the ignition front leaves biochar behind (Reed and Das, 1998). The primary objective in fast pyrolysis processes is production of bio oil and the amount of biochar produced would form only a meagre fraction of approximately 12 % of the total biomass. For obtaining a high bio oil yield, fast pyrolysis of feed stock needs to satisfy four conditions namely, a medium temperature (450 - 600 °C), high heating rate (103 - 104 K s^{-1}), short vapour residence time (< 2 s) and fast condensation of vapours (Cheng *et al.*, 2012). This leads to the implication that although a whole lot of biomass materials can be used to produce biochar, the production of biochar is mainly dependent on the method of production as well as the optimised conditions of synthesis including temperature, particle size, moisture content, type of biomass, nature or type of the reactor kiln and mode of operation. The small scale pyrolytic technologies available can be either manually operated or automated. In operating these technologies, it is possible to control some of the variables that have a bearing on the yield of biochar while it is not possible to directly control some operating conditions. The mode of operation would also exhibit variation according to the design of the reactors for either autothermal or allothermal mode.

The synthesis of biochar in present day high end industrial devices can be a highly automated process with low gas output (Peters *et al*., 2015). However, achieving the same results under rural tropical conditions, *i.e.,* with poorly maintained technologies in very low income settings is more challenging (Schmidt *et al.,* 2014). Traditionally, earth mound or earth covered pit kilns have been used most frequently. They are free of investment cost, merely requiring some poles and sand to cover the pyrolyzing biomass. However, they are slow (several days) (Duku *et al.,* 2011) and generate significant gas/aerosol emissions (Sparrevik *et al*., 2015). The CRIDA biochar kiln is used to produce biochar from maize, cotton and pigeon pea stalks on a small scale and the operational (process) parameters viz. loading rate, holding time and maximum conversion efficiencies were standardized for four bio residues. The biochar conversion efficiency of the kiln ranges from 24.4 % for castor stalk to 35 % for pigeon pea stalk (Venkatesh *et al*., 2013). Retort kilns involve a higher material investment and partially combust pyrolysis gases, reduce gas emissions by about 75% and have relatively high conversion efficiencies of 30-45 % (Adam, 2009). Biochar producing pyrolytic cook stoves such as TLUDs (Top Lit Up Draft) and Anila stoves (Adam, 2009) can synthesise biochar while providing heat for cooking. Advantages include clear burning thereby reducing indoor air emissions, using various biomass residues as biomass and with high fuel efficiency. Pyrolytic gases are mostly combusted in the flame front, reducing emissions of CO, CH_4 and aerosols by around 75 % (Jetter *et al*., 2012) compared to open fire or three stone cooking. Modern gasifier pyrolysis units come at a much higher investment cost but lead to the lowest emission factors and allow for the generation of electricity, avoiding electricity generation by off-grid fossil fuel generators (Peters *et al*., 2015). Of late, there has been an initiation of the Kon Tiki flame curtain kiln (Cornelissen *et al*., 2016), which is fast compared to traditional kilns (hours instead of days), cost effective and easy to operate. Flame curtain kilns come in two basic concepts: as a conical, all steel deep cone bowl and as a simple soil pit, consisting of a conically shaped hole in the ground which can be dug in a few hours and is essentially free of investment cost.

2.2 BIOCHAR CHARACTERIZATION

Biochar is characterised by an abundant surface area and enhanced porosity, which exhibits an upward trend with increasing pyrolytic temperature until around 850°C (Brown *et al.,* 2006). The pH of various biochar based materials are alkaline in nature (Spokas *et al.,* 2012), which can cause a decrement of soil acidity, facilitating a congenial niche for micro flora and fauna. Biochar also possesses an enhanced ability to adsorb cations and anions from solutions, particularly from polar and nonpolar organic compounds. Biochar synthesised from wood has a cation exchange capacity (CEC) up to 490 cmol kg^{-1} (Radlein *et al*., 1996) and an anion exchange capacity (AEC) of 88.2 cmol kg^{-1} (Fujita *et al.,* 1991). Lawrinenko and Laird (2015) reported that the AEC of biochar produced from four agro waste based biomass (maize stover, cellulose, alfalfa meal, and albumin) ranged from 0.602 to 27.76 cmol kg^{-1}, which exhibited an upward trend with decreasing pH and climaxing pyrolytic temperature. Cellulose based biochar, constituted wholly of C, H, and O possessed high AEC at pH 8 which points to the possibility of the occurrence of pH independent O containing functional groups that result in high AEC.

Pyrolysis efficiency of coconut husk biochar production was 37 %. Feedstock materials resulted in 40 % of <2 mm size biochar particles. The ash, low temperature volatile matter and apparent fixed carbon contents of coconut husk biochar were 16 %,

23

16 % and 68 %, respectively. Exchangeable K, available P, pH, EC and CEC of coconut husk biochar were 30281 mg kg^{-1}, 174 mg kg^{-1}, 10.24, 5.57 dS m^{-1} and 21.9 cmol kg^{-1}, respectively (Vasujini *et al.*, 2014).

Chemical parameters revealed that the biochar produced from birch wood had pH (9.6), EC (2.8 dS m^{-1}), CEC (9.26 cmol kg^{-1}), C (81%), N (0.24%), K (4.29 cmol kg^{-1}), Ca (6.24 cmol kg^{-1}) and Mg (0.40 cmol kg^{-1}) (Kumari *et al.* (2017).

The physico-chemical properties of biochar prepared under different conditions from selected feed stocks revealed that in corn cob biochar prepared at 350 °C, biochar recorded C content of 72.92 %, H content of 3.79 % and N content of 0.79 % and that produced at 400 °C had C content of 75.23 %, H content of 3.37 % and N content of 0.82 %. Biochar produced at 450 °C had C, H and N content of 77.84, 2.95 and 0.86 % respectively and that produced at 500 °C had C, H and N content of 80.85, 2.5 and 0.97 % respectively (Zheng *et al.*, 2010).

Shenbagavalli and Mahimairaja (2012) characterized biochar produced from different biological wastes, in a specially designed pyrolysis stove and reported that coconut shell biochar had pH of 9.18, EC of 0.73 dS m^{-1}, CEC of 12.50 cmol kg^{-1}, contents of total organic C 910 g kg^{-1}, total N 9.4 g kg^{-1}, C:N ratio of 96.8, P 3.2 g kg^{-1}, K 10.4 g kg^{-1}, Ca 8.5 g kg^{-1} and Mg 5.8 g kg^{-1}. Coir waste biochar had pH of 9.3, EC of 0.39 dS m^{-1}, CEC of 3.2 cmol kg^{-1}, total organic C 760 g kg^{-1}, N 8.5 g kg^{-1}, C:N ratio of 89.4, P 1.5 g kg^{-1}, K 5.3 g kg^{-1}, Ca 1.8 g kg^{-1} and Mg 1.4 g kg^{-1}.

Karim *et al.* (2015) evaluated the biochar from banana peduncle at 300 °C and reported that biochar yield, pH, moisture, volatile matter, ash content, fixed matter and total carbon were 66 %, 8.1, 26.28 %, 33.69 %, 24.84 %, 15.19 % and 37.79 %, respectively.

Lee *et al.* (2013) investigated the biochars provided from the following biomass residues by slow pyrolysis at 500 °C. Biochar made from coco peat exhibited pH of 10.30, ash content of 15.9 %, C 84.44 %, N content of 1.02 %, P content of 302 mg kg^{-1}, K 22,960 mg kg^{-1}, Ca 2667 mg kg^{-1}, Mg 544 mg kg^{-1}, Fe 2088 mg kg^{-1} and Mn 33 mg kg^{-1}. Paddy straw biochar produced was having properties like pH of 10.5, ash content of 52.37 %, C content of 86.28 %, N content of 3.25 %, P 3367 mg kg^{-1}, K content of 340 mg kg^{-1}, Ca content of 6018 mg kg^{-1}, Mg 2976 mg kg^{-1}, Fe 1956 mg kg^{-1} and Mn 1560 mg kg^{-1} whereas palm kernel shell biochar had pH of 6.9, 6.86 % ash content, 87.85 % C content, 1.11 % N content, 274 mg kg^{-1} P, 1219 mg kg^{-1} K, 19730 mg kg^{-1} Ca , 131 mg kg^{-1} Mg, 21380 mg kg^{-1} Fe content and 35 mg kg^{-1} Mn content.

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 8.6, ash content of 9.3 %, C content of 81.8 %, H content of 2.9 %, N content of 2.7 %, P content of 0.26 % and S content of 0.1 %. 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 were 67.51, 3.95, 1.01, 3.13, 0.37, 0.69, 0.24, 0.04 and 9.18 % respectively.

Jin *et al.,* (2014) found that biochar retained all heavy metals in sewage sludge except Arsenic, and the contents got magnified 2.5-3.5 times, whereas fast pyrolytic process hampered heavy metal leaching from biochar. Moreover, Agrafioti *et al.* (2013) found pyrolysis caused a decline of metal release in acetic acid extraction with pH of 5.9 and 6.0. Moreover, observations from leaching experiments also revealed that the concentration of heavy metals in the biochar leachate were considerably lower than those in sewage sludge (Zheng *et al*., 2013). He *et al*., (2010) opined that heavy metals exhibited immobility and stability in the constitutional fabric of biochar and that pyrolysis is capable of causing a decline in their prospective release. Lu *et al.,* (2015) while assessing the ratio of heavy metal content in biochar and sewage sludge, stated that 90.4 - 98.3 % of Pb, 96.4 - 99.5 % of Zn, 92.5 - 99.3 % of Ni, 85.5 - 92.5 % of As, 81.5 - 94.5 % of Cu and 70.0 - 87.5 % of Cr were retained in the pyrolytic product.

25

Kistler *et al.* (1987) also obtained identical results with the entire Cr, Ni, Cu and Zn being retained in the synthesised product within a temperature span of 350-750 °C.

Pandian *et al*. (2016) reported that the recovery percentage of *prosopis* biochar was highest (45-52 %) succeeded by cotton stalk biochar (38-46 %), red gram stalk biochar (36-39 %), while maize stalk biochar exhibited the lowest recovery percentage of 32-35 %. The mean conversion efficiency of 32-52 % biochar was realised and, furthermore, these differences are consequent to the type and density of the biomass substrate and pyrolytic temperature maintained. Of the various biomass substrates, biochar synthesised from *prosopis* had the highest pH value between 9.4 and 10.8 and electrical conductivity (EC) value of 0.83-1.25 dS m^{-1} and cotton recorded the lowest EC of 0.58-0.85 dS m^{-1}. Of the various biomass substrates, *prosopis* biochar proved to be the most alkaline in nature(10.8) while cotton stalk biochar exhibited a low level of salinity (0.58-0.85 dS m^{-1}), than the other biomass substrates (0.85-1.09 dS m^{-1}) which were characterised by moderate level of salinity. The content of organic carbon content of *prosopis* biochar was 25-32 g kg^{-1}, 21-76 g kg^{-1} in maize stalk biochar, 24-76 g kg^{-1} in red gram stalk biochar and 17-69 g kg^{-1} in cotton stalk biochar. With regard to the organic carbon content of biochar, red gram stalk biochar and maize stalk biochar recorded the highest content (76 g kg^{-1}) succeeded by cotton stalk biochar (69 g kg^{-1}). Highest available N (0.79×10^{-2} mg kg^{-1}) was seen in maize stalk biochar and available P (0.018×10^{-2} mg kg^{-1}) and K (5×10^{-2} mg kg^{-1}) were rich in maize stalk biochar and these changes were mainly due to the type of biomass substrate and their elemental constitution. There was a variation of 66 % to 89 % of total carbon content resulting primarily from the accumulation of carbon during pyrolysis and the inherent carbon content of the feedstock bio-waste. The variation of 0.19% to 0.45 % was seen in total N and the biochar produced from maize stover recorded the highest total N (0.45 %) and total P of 0.84 % and red gram stalk biochar registered the highest total K of 2.5 %. The lowest total N (0.19 %), total P (0.23 %) and total K (0.5 %) were registered in the *prosopis* biochar. From the above research information, it can be concluded that the differences in elemental constituents of different biochar materials is primarily influenced by the source of biomass substrates.

2.3 EMERGING APPLICATION OF SYNGAS FOR ENERGY PRODUCTION

Biochar based materials have been studied for the catalysis of refinery processes (e.g., syngas cleaning and syngas conversion), biodiesel production, as well as air pollution control (Lee *et al.*, 2017). Emitted gases during the process include methane (CH_4), carbon monoxide (CO), aerosols (smoke; $PM_{2.5}$ and PM_{10}), nitrogen oxides (NOx), as well as non-methane volatile organic matter, in addition to hydrogen. CO, aerosols and NO_x are harmful to human health (Kampa and Castanas, 2008), and methane and aerosols can exacerbate anthropogenic radiative forcing (Forster *et al.*, 2007).

Syngas derived from thermochemical conversion of biomass contains CO, H_2, CO_2, and volatile hydrocarbons, which can be upgraded into fuels through different processes. The biochar-based carbon encapsulated iron nanoparticle catalyst promoted Fischer Tropsch synthesis (FTS) effectively, achieving 95 % CO conversion and 68 % liquid hydrocarbons selectivity (Yan *et al.*, 2013). Besides, activated biochar loaded with ruthenium facilitated methanation, in which 97 % CO and 55 % CO_2 in syngas were converted to give a CH_4 yield of 54 % (92 % selectivity) under sufficient H_2 supplement (Wang *et al.*, 2014).

Hydrogen is another sustainable alternative to fossil fuels in view of its low emissions, which can be produced via biogas reforming. Wood biochar achieved 70 % CH_4 conversion within 120 minutes at 1000 °C in the presence of CO_2 and steam as the pyrolysis gas (Dufour *et al.*, 2008). In such a case, biochar was continuously regenerated to maintain high surface area and accessible pore structure via the oxidation of carbon by CO_2 and H_2O at high temperature. Similarly, the CO_2 treated duckweed derived biochar obtained 82 % and 25 % conversion of CO_2 and CH_4 at the early stage of biogas reforming, respectively (Muradov *et al.*, 2012). The results outcompeted the

27

untreated biochar (42 % and 10 % conversion of CO_2 and CH_4) which had significantly lower surface area compared to the CO_2 treated one (5-12 *Vs* 60 $m^2 g^{-1}$). Nevertheless, the latter lost its initial activity of ~90 % due to blockage of the active sites by carbon deposition. It was suggested that the unsaturated carbon atoms, which originated from the thermally decomposed surface oxygen functional groups, served as the active sites for the chemisorption and decomposition of CH_4 (Dufour *et al*., 2008). The biochar catalyst gave similar performance before and after demineralization in the same study, suggesting the negligible role of ashes for promoting methane decomposition. Interestingly, this contrasted the result of methane decomposition process for tar reforming (Klinghoffer *et al*., 2015). In addition, pyrolytic waste tire biochar achieved 95 % conversion of methyl cyclohexane to hydrogen upon wetness impregnation of Pt nanoparticles in the micro regions (Zhang *et al*., 2011), which may apply to catalytic methane to hydrogen process.

2.4 BIOCHAR AND CARBON SEQUESTRATION

Terra preta soils contain large carbon reservoirs as studies indicate that up to 70 times more carbon has been found in these soils in comparison to surrounding Oxisols (Glaser *et al.,* 2001). Although afforestation still remains a feasible way of sequestering carbon by photosynthesis, the process is only carbon neutral. In contrast, the application of biochar to soils has the added advantage of turning carbon sequestration into a carbon negative system (Lehmann, 2007). This means that, because biochar is very slow to decompose, and yields a high carbon output over time, it is an effective, viable and sustainable carbon sequestration option (Vaccari *et al.,* 2011).

The application of biochar for C sequestration in agricultural soils is a feasible option as a part of climate change mitigation strategies (Sohi *et al*., 2010; Vaccari *et al.,* 2011). Considering that methane (CH_4) and nitrous oxide (N_2O) gas emissions are generally high and pose a huge threat globally to agricultural management, the potential effect of biochar to draw CO_2 from the atmosphere, has been proposed as significant quantity in dealing with greenhouse gas emissions (Sohi *et al.,* 2010).

As most cultivated agricultural soils are depleted of soil organic carbon (SOM) (Vaccari *et al.,* 2011), amendment with biochar may provide the benefits of being long term sinks for the withdrawal of CO_2 (Sohi *et al.* 2010), and further producing large amounts of renewable bio energy (Laird *et al*., 2010). Lehmann (2007) suggests that the pyrolysis of inexpensive feedstock can also contribute to emissions reductions when the pyrolysis gases are captured for bio energy production. Cumulatively, these advantages serve as efficient means for climate change mitigation (Sohi *et al*. 2010). However, the exclusive use of biochar is not suggested. Instead, as an all-encompassing strategy, it is recommended that biochar be used in conjunction with alternate climate change mitigation strategies to help in better reducing greenhouse gas emissions (Verheijen *et al*., 2010).

Biological feedstocks with high lignin concentrations have been reported to possess a high carbon recovery and mineral content (Raveendran *et al*., 1995). This is demonstrated in a study conducted by Novak *et al*. (2009) where it was shown that no significant loss of soil organic carbon took place during incubation studies with pecan shell derived biochar. Instead, the soil had an increase of 11.8 g C kg^{-1} after being mixed with a level of 2 % biochar, and thus suggesting that the addition of biochar has the potential to efficiently sequester carbon.

Decomposition of biochar occurs at different rates and by different processes, and is dependent on the feedstock and pyrolysis conditions (Zimmerman, 2010). The degradability of the feedstock is dependent on the recalcitrant nature of biochar, and can be influenced by biological and chemical conditions (Glaser *et al.,* 2001). However, black carbon rich soils can be decomposed over time by abiotic and microbial oxidation (Zimmerman, 2010).

The compounded effects of an increasing global population, diminishing food reserves and climate change are a global growing concern (Lehmann and Joseph, 2009). Since food security partly depends on the sustainability of good agricultural soil practices, Whitman and Lehmann (2009) suggested that soil biochar amendments could most likely contribute towards improved agronomic and environmental developments and the alleviation of climate change. Further, considering that CO_2, CH_4 and N_2O pose a major threat to global warming (Lehmann, 2007), the effect of biochar to contain and potentially reduce these emissions warrants further investigation as the current evidence has been sparsely assessed (Sohi *et al.*, 2010).

2.5 EFFECTS OF BIOCHAR APPLICATION ON SOIL HEALTH

It has been reported that biochar application to the soil boosts soil fertility, improve soil quality and increases crop yields. Soil benefits include increases in soil pH, water holding capacity (WHC), cation exchange capacity (CEC) and nutrient retention (Novak *et al.,* 2012). Biochar is a low cost product and has been tipped as an excellent soil amendment for sequestering carbon, for increasing soil organic carbon content, water retention properties and to provide a suitable medium for soil microbes (Stavi and Lal, 2013).

2.5.1 Effects of Biochar Application on Physical Properties of Soil

Owing to the highly porous nature of biochar, soil application of biochar would ultimately lead to an enhancement of a wide range of soil physical properties like total porosity, pore size distribution, soil density, soil moisture content, water holding capacity/plant available water content and infiltration/hydraulic conductivity (Atkinson *et al.*, 2010).

The enhancement in particle surface area and storage of water within its porous structure enables biochar to improve the WHC of soil (Lehmann *et al.*, 2003). Application of biochar (5 t ha^{-1}) increases WHC by 2.5 % in a sandy loam textured soil at the surface soil layer (Pandian *et al*., 2016). 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) did a study where WHC was enhanced from 11.3 % for untreated control soil to 15.5 % for soil treated with rice husk biochar. Southavong and Pretson (2011) reported that biochar application enhanced WHC of soil from 43 to 53 % and 40 to 50 %, respectively. Southavong *et al*. (2012) investigated the impact of biochar and biodigester effluent on soil fertility changes and biomass production of water spinach. It concluded that application of biochar @ 40 t ha^{-1} iimproved WHC of the soil by 40-60 % and soil pH from 4.68 to 6.22.

Jones *et al*. (2012) concluded that addition of 40 and 80 t ha^{-1} of green waste biochar to bauxite processing residue coarse sand had a marked declining effect on macro porosity (pore diameters >0.29 μm) while significantly improving meso porosity (pore diameters between 0.20 and 0.29 μm). This is due to biochar partially filling the voids existing within the coarse sand particles. Belyaeva and Haynes (2012) also found that application of biochar at enhanced rate (50 or 100 t ha^{-1}) greatly decreased macro porosity and increased meso porosity and in some cases micro porosity. Consequently there was a considerable enhancement in the water holding capacity. Total porosity was enhanced by 2 % and available WHC 3 % in medium textured soil by the application of biochar @ 5 t ha^{-1} (Pandian *et al*., 2016).

Zhang *et al*. (2010) observed that the wheat straw biochar addition had a depressing effect in the bulk density of a rice paddy soil at 40 t ha^{-1}. Liu *et al*. (2012) suggested that the addition of 8-16 g kg^{-1} of sawdust biochar significantly enhanced the aggregate stability. Pandian *et al*. (2016) reported that bulk density got reduced from 1.41 to 1.36 g cm^{-3} in medium textured soil by the amelioration with biochar @ 5 t ha^{-1}. Decreased bulk density, enhanced porosity and saturated water content were resulted by the addition of acacia green waste biochar at rate of 47 t ha^{-1} (Hardie *et al*., 2014). Githinji (2014) evaluated the effect of biochar application rate on physical properties of a sandy loam amended at different rates (25, 50, 75 and 100 % v/v) of biochar. The results showed that bulk density decreased from 1.32 to 0.36 g cm^{-3} with porosity increasing from 0.50 to 0.77 cm^3 cm^{-3}. Thus, it can be concluded that biochar addition has prominent effects on improved soil physical properties on sand/sandy loam textured soils.

2.5.2 Effects of Biochar Application on Chemical Properties of Soil

Biochar has potential benefits in improving the chemical properties of soils. Research findings indicate significant changes in soil quality that include increases in pH, organic carbon, exchangeable cations, and N fertilizer use efficiency and also a decline in tensile strength at enhanced biochar rates >50 t ha^{-1} (Bera *et al.*, 2016). For example, application of paper-mill biochar at the rate of 10 t ha^{-1} in a Ferrosol significantly increased pH, CEC, exchangeable Ca, total C, and reduced, the exchangeable Al availability, while in a Calcarosol, it enhanced C and exchangeable K (Van Zwieten *et al.,* 2015).

Chintala *et al.* (2014) conducted an incubation study in an acidic soil (clayey, smectitic, acid, mesic, shallow, Aridic Ustorthent) of pH < 4.80 for a period of 165 days to investigate the influence of biochar application on chemical parameters such as soil pH, EC, CEC and exchangeable acidity. The biochars were synthesised from two different biomass substrates, namely corn stover and switchgrass and were incorporated at the rate of 52, 104 and 156 t ha^{-1} to acidic soil. The produce from corn stover markedly improved the EC of acidic soil by 21, 40 and 83 % in accordance with an increment in in the incorporation rate from 52, 104 and 156 t ha^{-1}, while that from switchgrass resulted in enhancement of EC of soil by 19, 51 and 57 % in accordance with an increment in in the incorporation rate from 52, 104 and 156 t ha^{-1}, respectively. The increment effected in soil pH was by 0.73, 0.99 and 1.36 units with the addition of corn stover biochar at 52, 104 and 156 t ha^{-1}, respectively, whereas the increment effected in soil pH was by 0.49, 0.74, and 0.91 units with the addition of switchgrass biochar at 52, 104 and 156 t ha^{-}. Corn stover biochar addition resulted in a significantly higher rae of pH increase in comparison with switch grass biochar.

Pandian *et al.* (2016) reported that addition of *prosopis* biochar 5 t ha^{-1} increased soil pH from 5.7 to 6.3. The increase in soil pH in the biochar added soil is basically from the alkaline pH (8.4-10.8) of biochar. Nigussie *et al.* (2012) concluded that the highest soil pH (5.44) and EC (0.26 dS m^{-1}) were observed in soils treated with 10 t ha^{-1} biochar.

Van Zwieten *et al.* (2010) investigated with two biochars from papermill waste with pH values 8-9, and a liming value of around 30 % that of $CaCO_3$. With an addition of 10 t ha^{-1} of these biochars to a Ferralsol soil in a greenhouse experiment, the increase in pH effected was from 4.20 to 5.90. Jeffery *et al.* (2011) observed an increment in soil pH of 0.10 to 2.0 units after biochar addition to soils that have a large span of pH values. Masto *et al.* (2013) did a field experiment in an acidic red soil to study the impact of lignite fly ash and biochar on soil nutrient elements, biological attributes and the productivity of maize and found that biochar addition @ 2 t ha^{-1} and 4 t ha^{-1} enhanced pH from 6.09 to 6.64.

Pandian *et al.* (2016) concluded that the addition of red gram biochar 10 t ha^{-1} increased cation exchange capacity to 1.4 cmol kg^{-1} and improved the carbon build up by 4.4 t ha^{-1}. Ippolito *et al.* (2012) demonstrated the rose in CEC of soil consequent to biochar addition, and this ultimately led to increase in soil fertility and decreased fertilizer runoff. Increment in CEC of up to 40 % over initial CEC by biochar application was observed by Topoliantz *et al.* (2002). 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 biochar soils and concluded that CEC per unit soil C increased to 1.90 times higher in Anthrosols than in the adjoining areas. The charge density (potential CEC per unit surface area) was higher in more biochar contained Anthrosols than adjoining soils. Moreover, a high specific surface area owing to the presence of biochar, which would have also contributed to the high CEC reported in soils with high biochar content. Anthrosols contained soil organic matter with 55 to 238 % increased aromaticity than adjoining soils and thermal oxidation were 23 to 355 % higher in Anthrosols than adjoining areas.

Van Zwieten *et al.* (2010) assessed the addition of biochar @ 10 t ha^{-1} in a ferrosol and found that the total soil carbon significantly rise to 0.50 %. Sukartono *et al.* (2011) did an experiment to assess the influence of biochar application on soil fertility status, nutrient uptake and productivity of maize in sandy soils of Indonesia and the study revealed that addition of biochar @ 15 t ha^{-1} improved the soil organic C from 0.90 to 1.20 %. Masto *et al.* (2013) concluded that incorporation of biochar @ 2 and 4 t ha^{-1} significantly increased the soil organic C from 0.81 % in control to 1.17 and 1.00 % at biochar and biochar + lignite fly ash treatment, respectively.

Chintala *et al.* (2014) investigated the addition of biochar improved the concentration of macro and micronutrients than in the control soils. The most noticeable increase in contents of Ca, K, Mg and P was observed in soils amended with biochar from woodchips, newspaper and cardboard. Pandian *et al.* (2016) concluded that the biochar addition @ 5 t ha^{-1} enhanced soil available nitrogen by 25 % which varied from 158 to 178 kg ha^{-1}. The retaining of nutrient elements in soils incorporated with biochar may be ascribed to the sorptive capacity of newly added biochar through charge or covalent interactions (Major *et al.*, 2009).

Rondon *et al.* (2007) performed an experiment to examine the potential, magnitude and reasons of increase in biological N_2 fixation by common beans (*Phaseolus vulgaris* L.) through biochar application and concluded that biochar @ 90 g kg^{-1} increased the proportion of fixed N from 50 % to 72 % and improved the availability of P, K, Ca, B and Mo. Sika (2012) conducted a leaching experiment in sandy soils using biochar and concluded that biochar application @ 0.50, 2.50, and 10.0 % w/w brought about a marked decrease in leaching of ammonium (12, 50 and 86 % respectively) and nitrate (26, 42 and 95 % respectively) fertilizer in an sandy soil.

Additionally, biochar (0.50 %) markedly brought about a decrease in the leaching of basic cations, phosphorus and certain micronutrients. Huang *et al*. (2013) conducted an experiment to quantify the effect of biochar amendment on soil quality and crop productivity in Chinese rice fields and concluded that the addition of biochar @ 10, 20 and 40 t ha^{-1} to paddy soils led to increase in soil total N by 10 % and a decrease in soil bulk density by 9 %, on an average basis in comparison with control treatment.

Lehmann *et al*. (2003) demonstrated that while biomass yield and N uptake of cowpea improved with large amounts of biochar applications, plant N content declined. With selective additions of biochar augmented with nutrient content additives nitrogen supply to agricultural systems can be enhanced without an apparent decline in crop yields. Such a soil management strategy would be of relevance particularly in a scenario of mixed legume cereal intercropping or of agro forestry with woody legumes. The reserve of soil nitrogen and gradually nitrogen availability can thus be enhanced and also be made available to the non-legume in a crop rotation oriented practise.

Masto *et al*. (2013) did a field experiment in an acidic red soil to study the impact of lignite fly ash and biochar on soil nutrients, biological attributes and productivity of maize. Application of biochar @ 2 and 4 t ha^{-1} increased soil P and K availability by 110 and by 64 % respectively. Widowatil and Asnah (2014) performed a field investigation to assess the influence of biochar @ 30 t ha^{-1} synthesised from organic waste, on K fertilizer leaching and uptake, the degree of retentive and utilisation capability associated with of K fertilizer addition, and economic feasibility of farming maize in an Inceptisol. The outcome of the study suggested that biochar has the capability to substitute and to a large extent decrease KCl fertilizer addition. Biochar addition was found to enhance the available content of nutrient elements by 69 to 89 % for K^+, 61 to 70 % for Ca^{2+}, 39 to 53 % for N total, 179 to 208 % for P (Widowatil and Asnah, 2014).

Biochar can also increase endo mycorrhizal plant associations and enhancing P availability (Garcia-Montiel *et al.*, 2000). Application of biochar (10 t ha^{-1}) on chromium polluted and unpolluted soils significantly increased the mean values of soil organic C, total N, available phosphorous and available potassium values of 3.31 %, 0.49 %, 34.09 mg kg^{-1} and 56.87 mg kg^{-1} (Nigussie *et al.*, 2012). Tammeorg *et al.* (2014) reported that addition of 10-25 t ha^{-1} of biochar of woody raw materials has enhanced the content of potassium of non-weathered temperate soils (Liu *et al.*, 2012), while there was no marked impact for available P, Ca, Mg and S after the elapse of 1-3 years after incorporation. Coumaravel *et al.* (2015) observed that on an average, an increase of 15.7,10.8 and 2.2 % of available N, 52.1, 32.6 and 4.7 % of available P and 18.1,14.3 and 4.3 % of available K respectively was recorded for biochar with IPNS, biochar with NPK alone and biochar alone treatments over the corresponding nutrient initial status.

Van Zwieten *et al.* (2010) reported that the biochar addition @ 10 t ha^{-1} in a ferrosol significantly increased exchangeable Ca levels from 1.23 cmol kg^{-1} to 8.87 cmol kg^{-1}. Major *et al.* (2010b) investigated the effect of a one time addition of 0, 8 and 20 t ha^{-1} of biochar tin a Colombian savanna Oxisol for 4 years and the results showed that the Ca and Mg availability was 77 to 320 % greater with biochar treatments. Prabha *et al.* (2013) noted that with the addition of biochar 35 g pot^{-1}, N rose by 60 % and a remarkable increase of 63, 29 and 38 % were registered for P, K and total nitrogen as compared with control. Chen *et al.* (2011) reported an increase of Cu^{2+} and Zn^{2+} adsorption capacities by 12.52 and 11.0 mg g^{-1} for corn straw biochar, 6.79 and 4.54 mg g^{-1} for hard wood biochar, respectively from aqueous solution.

2.5.3 Effects of Biochar Application on Biological Properties of Soil

Since pyrolysis ensures complete sterility, any immediate bearing on the biotic microbes is their elimination during pyrolysis, (Thies *et al.*, 2015). On the other hand, the high porosity of biochar may have an indirect favourable bearing to microbes which indirectly increase soil microbial biomass and basal activity (Lehmann *et al*., 2015) by ensuring a protected and aerate environment for microbial growth (Schmalenberger and Fox, 2016). There can be other cases too in which biochar can have a direct bearing in amending soil microbial population fabric by ensuring the needed nutrient supply (Schmalenberger and Fox, 2016). The enormous internal surface area of biochar expands the organic and inorganic compound adsorption capability of soil, in a way that there is an enhanced supply of mineral nutrients and energy to microbial population facilitating their proliferation (Gul *et al*., 2015).

The abundant porosity of biochar enables soil microbes to proliferate, without being accessible to their predators. Moreover, these surfaces sorb inorganic nutrients well as organic substances and gases that create a congenial condition for the growth and development for microbes. Even though there is a variation in the pore size of biochar, it is generally sufficient to enable the proliferation of a host of soil inhabiting microorganisms (Thies and Rillig, 2009). It is primarily the soil microorganisms that are accountable for setting in the nutrient elemental cycling, whereby, soil organic matter is ingested and converted (mineralization) into substances that can be taken up by plants. Secondly, the decomposition of soil microbes which augment the soil organic C pool, which is vital for the sustenance of soil health. The tertiary benefit is that some beneficial soil microorganisms, such as mycorrhizal fungi, engage in symbiotic relationships with plants to form either intracellular (AMF) or extracellular (ectomycorrhizal fungi) associations with plant roots.

Masto *et al*. (2013) reported that the application of biochar @ 2 and 4 t ha^{-1} increased activity of microbes reflected by enhanced dehydrogenase activity (60.70 %), alkaline phosphatase (32.20 %), fluorescein hydrolases activity (12.30 %) and microbial biomass (25.30 %) increased. Oleszczuk *et al*. (2014) reported that the incorporation of biochar to the soil caused a remarkanble enhancement in the activity of dehydrogenases, urease, protease and alkaline phosphatase in relation to the biochar rate (30 and 45 t ha^{-1}) by 168 and 71 % (dehydrogenases), 77 and 127 % (urease), 74 and 7 % (protease) and by 198 and 120 % (alkaline phosphatase) respectively.

2.6 EFFECT OF BIOCHAR APPLICATION ON CROP PRODUCTION

Application of 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 (Bera *et al.*, 2016; Hussain *et al.*, 2017) (ii) increased in soil pH (Chintala *et al.*, 2014) (iii) increased soil CEC (Chintala *et al.*, 2014) (iv) improvement soil physical properties (Pandian *et al.*, 2016), including an increase in soil water retention and (v) alteration of soil microbial populations and functions (Azeem *et al.*, 2016). These effects may also act in concert to result in improved crop performance.

2.6.1 Plant Nutrient Concentration and Uptake

Application of biochar @ 20 t ha^{-1} + 2% PGPR + NPK increased total N (52.80 %), K (91.89 %), Ca (28.7 %), Mg (64.62 %), S (93.19 %), Zn (59.33 %) and Cu (78.03 %) content in cowpea shoot as compared to control treatment at harvest stage (Dainy, 2015).

Chan *et al.* (2007) studied an increase in the uptake of N at higher levels of biochar. Since nitrogen is primarily assimilated by plants as nitrate (NO_3^-), it is imperative that its uptake be coupled with an uptake of basic cations in order to maintain electrical balance. Consequently, this is associated with a considerable increase in K uptake, and a slight increase in Ca uptake. Lehmann *et al.* (2003) attributed the increased plant growth responses observed to greater plant uptake of K, P, Ca, Zn and Cu with increasing biochar applications.

Plant nutrient uptake and availability of nutrients such as P, K and Ca are typically increased, while free Al in solution decreased in solution in biochar amended soils. This occurs as a function of biochar's high porosity and surface to volume ratio, together with an increase the in the pH of acid soils, attributed to the basic compounds found in biochar (Chan *et al.*, 2007).

Widowatil and Asnah (2014) studied a field experiment to the effect of biochar @ 30 t ha^{-1} prepared from organic waste, on potassium fertilizer leaching and uptake, efficiency and effectiveness of potassium 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 % as compared to the sole application of KCl fertilizer (5.45 t ha^{-1}) and dual application of biochar and 75 % dosage of KCl fertilizer application increased maize production by 29 %. Application of biochar and KCl fertilizer @ 50 kg ha^{-1} resulted in the highest relative agronomic effectiveness (137 %) and K fertilizer efficiency (18 %).

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

Biochar reduces leaching and at the same time efficacy, as it limits both biodegradation and plant uptake (Kuppusamy *et al.*, 2016). This eventually increases pesticide residual life in soil and negatively affects soil micro biota. Similarly, absorption capacity of biochar has a potential to mitigate the bioavailability of heavy metals in contaminated soils (Herath *et al.*, 2015; Hossain *et al.*, 2015). Clearly, the capacity of biochar to adsorb a range of contaminants (both organic and inorganic) may lead to an imbalance in the uptake of plant nutrients and may affect product quality (Kuppusamy *et al.*, 2016).

2.6.2 Plant Growth and Yield

A combination of biochar ability to raise soil pH improve physical properties such as water holding capacity and retain soil nutrients and reduce leaching losses are likely contribute to its ability to increase cowpea crop productivity (Dainy, 2015). 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 and ash, supplying important plant nutrients such as K, N, Ca and P. Biochar typically increases pH of acidic soils due to the liming capacity of associated carbonate salts retained in the ash component of biochar (Van Zwieten *et al.*, 2010). 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).

Biochar addition to the soil has a positive effect by improving the soil water and nutrient status. The application of biochar along with inorganic fertilizer or meat bone meal in an Endogleyic Umbrisol have increased the plant available water content, soluble K and organic carbon but had no effects on other soil nutrients, pH or moisture content. The biochar addition had not influenced the N uptake, grain yield or quality of wheat (Tammeorg *et al.*, 2014). In tomato plants, biochar addition @ 25 and 50 t ha^{-1} improved soil water storage and enhanced the growth, physiology and yield of tomato. Biochar significantly increased soil organic matter and total nitrogen, while soil nitrate nitrogen and ammonium nitrogen levels were decreased significantly (Agbna *et al.*, 2017).

Yield increases with biochar application have been documented under controlled environments as well as in the field (Chan and Xu, 2009). Reported biochar application rates ranged from less than 1 t ha^{-1} to over 100 t ha^{-1}, and reported percent of tomato yield increases over respective controls ranged from less than 10 % to over 200 %. Biochar applications to soils may increase seed germination, plant growth and crop yields (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 (Van Zwieten *et al.*, 2010)

Biochar has been reported to have both direct and indirect influence on soil nutrient availability, which can have impacts on plant growth (Blackwell *et al.*, 2009). 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 (Gaskin *et al.*, 2010).

Prabha *et al.* (2013) found that in wetland rice soils, application of biochar in appropriate proportion has a significant influence over the soil carbon dynamics by increasing the major soil carbon sequestration parameters like soil organic carbon, particulate organic carbon and microbial biomass carbon and has the ability to combat global warming without affecting the rice productivity. Major soil carbon sequestration parameters were found to be higher under biochar treatment. Biochar applications considerably influenced the growth profile and grain yield of the rice plants as compared to other amendments. Biochar of appropriate applied proportion can influence wetland rice soil carbon dynamics and has the potential to combat global warming without compromising productivity.

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 % 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 (10.6 %) than for paddy rice (5.6 %). Generally, greater positive responses were observed in experiments with legumes, vegetables and grasses. The average increase in crop productivity was 30.3, 28.6 and 13.9 % respectively for legume crops, vegetables, and grasses and 8.4, 11.3 and 6.6 % respectively for maize, wheat, and rice. Yield increases with application of biochar were greater than biomass increases for maize, whereas, the reverse was true for wheat.

Agegnehu *et al.* (2017) revealed that the combination of biochar along with compost is found to be more effective in improving the soil properties and crop yield than biochar alone. In sandy acidic soils, conservation farming and biochar amendment is found to be a promising combination for increasing harvest yield. Moderate but non-significant effects on yields were observed for maize and wood biochar in a red sandy clay loam ultisol (Cornelissen *et al.*, 2016). Different soil properties like soil water content, CEC, K, Ca, NO_3, NH_4 and organic carbon content were improved by biochar, compost and co-composted biochar amendments, but all these amendments have decreased the banana yield by 18, 12 and 24 % respectively whereas no significant effect was witnessed on the yield of papaya. Thus improvement in soil nutrient and soil physical properties did not translate to improve fruit yield (Bass *et al.*, 2016).

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 %, respectively. Glaser *et al.* (2002) observed that biochar @ 67 t ha^{-1} and 135 t ha^{-1} char increased biomass by 150 % and 200 % respectively in cowpea on Xanthic Ferralsol. In a pot experiment, Lehmann *et al.* (2003) found biochar to increase rice biomass by 17 % and cowpea by 43 % 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.

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 @ 67.6 and 135.2 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 % without fertilization.

Chan *et al.* (2007) reported that in a pot trial a significant increase in the dry matter production of radish was observed when N fertilizer was used together with biochar. The results showed that in the presence of N fertilizer, there was a 95 to 266 % variation in yield under 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 was thus shown as a major positive attribute due to the application of biochar (Chan and Xu, 2009).

Biochar application has also been found to reduce the incidence of crop disease and mitigate biotic stress (Gwenzi *et al.*, 2015; Haider *et al.*, 2015). Sarma *et al.* (2017) reported that the addition of biochar recorded lower benefit cost ratio (3.5 and 3.8) but its application with inorganic fertilizers recorded the highest agronomic efficiency signifying potentiality to uphold efficient nitrogen use and environmental sustainability. Thus, addition of biochar in acidic soil would be a sustainable option to reduce carbon mineralization and increase crop productivity.

Hamdani *et al.* (2017) concluded that 1.0 % biochar along with reduced fertilizer doses, could be effectively used to improve wheat growth, yield, nutrient content and nutrient uptake under field condition. Moreover, 1.0 % biochar along with 75 % of inorganic fertilizers can be effectively used in place of 100 % inorganic fertilizers to get the highest yield.

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. Lehmann (2007) studied that 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 biochar additions up to 50 Mg ha^{-1} and may show growth reductions only at very high applications.

It is reported that black carbon can produce significant benefits when applied to agricultural soils in combination with some fertilizers. Increase in crop yield to the tune of 45-250 % has been reported by application of biochar along with chemical fertilizers (Jha *et al*., 2010).

MATERIALS AND METHODS

3. MATERIALS AND METHODS

An investigation was carried out at College of Agriculture, Vellayani during March 2015 to June 2016. The objective was to 'Refine the technology for micro level biochar production from tender coconut husk and evaluation of its effect on soil health, yield and quality of banana (*Musa* spp.)'. The whole study was conducted in two parts.

Part I Refinement of biochar production technology

Part II Field experiment for evaluation of biochar on soil health, yield and quality of banana

3.1 REFINEMENT OF BIOCHAR PRODUCTION TECHNOLOGY

For the refinement and enhancement of the efficiency of the existing biochar production unit developed at the Department of Soil Science and Agricultural Chemistry during 2015, a modified double barrel micro biochar kiln was designed and fabricated indigenously for the pyrolytic conversion of dried tender coconut husk to biochar. The micro biochar kiln was developed with pyrolytic temperature measuring probe. Syngas, a major by-product of pyrolysis was collected in tedler bags after water jacket cooling. The whole modification in the micro biochar kiln took about 6 months for completion (March, 2015 to July, 2015). The specifications and fabrication procedure of the developed micro biochar kiln is explained in the results chapter.

3.1.1 Biochar Characterization

The biochar produced from tender coconut husk by using the modified technology was assessed for electro-chemical and chemical properties as per standard methodologies outlined in Table 1.

Table 1. Standard analytical methods for characterization of biochar

Parameter	Method	Reference
pH (1:20)	Potentiometry (Biochar:water (1:20) and equilibration for 90 minutes in shaker)	Rajkovich *et al.* (2011)
EC (1:20)	Conductometry (Biochar:water (1:20) and equilibration for 90 minutes in shaker)	Rajkovich *et al.* (2011)
Cation Exchange Capacity	Neutral 1 *N* NH_4OAc extraction and distillation	Jackson (1973)
Anion Exchange Capacity	$BaCl_2$-$Ca(OH)_2$, pH 8.0 extraction and measurement using spectrophotometry	Bunzl and Sansoni, (1976)
Total organic carbon	TOC analyzer	Piper (1966)
N	Microkjeldahl distillation after digestion in H_2SO_4	Jackson (1973)
P	Nitric-perchloric (9:4) acid digestion and vanado-molybdo yellow color method and measurement using spectrophotometry	Greenberg *et al.* (1992)
K	Nitric-perchloric (9:4) acid digestion and flame photometry	Jackson (1973)
Ca, Mg	Nitric-perchloric (9:4) acid digestion and atomic absorption spectrophotometry	Jackson (1973)
Fe, Mn, Zn, Cu	Nitric-perchloric (9:4) acid digestion and atomic absorption spectrophotometry	Jackson (1973)
S	Nitric-perchloric (9:4) acid digestion and turbidimetry	Tabatabai (1982)
B	Dry ashing at 550 ^{0}C in silica crucibles followed by extraction of ash in 10 ml of 0.36 N H_2SO_4 for one hour at room temperature and filtration through Whatman No. 42 filter paper. Spectrophotometry	Roig *et al.* (1988)
Pb, Cd, Cr, Ni	Nitric-perchloric (9:4) acid digestion and emission spectroscopy (ICP-OES)	Wei and Yang (2010)

3.1.2 Syngas Analysis

Analysis of the composition of syngas produced during pyrolysis was done by micro gas chromatography (Agilent Technologies 490 micro GC), in order to study whether it can be used as a bioenergy source or not.

3.2 FIELD EXPERIMENT

The field experiment was carried out to investigate the efficacy of biochar from tender coconut husk for on soil health, yield and quality of banana.

3.2.1 Generation of Soil Test Based Fertilizer Recommendation for Banana

Composite soil samples were drawn from experimental site (Block D) of the Instructional Farm, College of Agriculture, Vellayani. Soil samples were analyzed for pH, OC content, major (N, P, K), secondary (Ca, Mg, S) and micronutrients (Fe, Mn, Zn, Cu, B) following standard procedures (Table 2). Based on the analytical results, the package of practices recommendations of Kerala Agricultural University was modified and soil test based recommendation worked out from the soil fertility rating classes for each nutrient (KAU, 2016). The data on soil test are given in the results chapter.

3.2.2 Experimental Site and Season

A field experiment was laid out in the Block D of the Instructional Farm, College of Agriculture, Vellayani with banana as test crop/variety Nendran. The experiment was conducted during September 2015 to June 2016.

3.2.3 Location

The field experiment was carried out at College of Agriculture, Vellayani. The site situated at 8^0 25’46” N latitude and 76^0 59’24’’ E longitude and at an altitude of 19 m above MSL (Plate 1).

Table 2. Analytical procedures followed for soil analysis in the experimental field

Parameter	Method	Reference
Physical properties		
Water holding capacity	Core method	Gupta and Dakshinamoorthy (1980)
Bulk density	Core method	Gupta and Dakshinamoorthy (1980)
porosity	Core method	Gupta and Dakshinamoorthy (1980)
Chemical properties		
pH (1:2.5)	Potentiometry	Jackson (1973)
EC (1:2.5)	Conductometry	Jackson (1973)
Cation Exchange Capacity	Neutral 1 *N* NH_4OAc extraction and distillation	Jackson (1973)
Organic carbon	Walkey and Black's rapid wet titration method	Walkey and Black (1934)
Available N	Alkaline potassium permanganate method	Subbiah and Asija (1956)
Available P	Bray No.1 extraction and spectrophotometry	Jackson (1973)
Available K	Neutral 1 *N* NH_4OAc extraction and flame photometry	Jackson (1973)
Available Ca, Mg	Neutral 1 *N* NH_4OAc extraction and Atomic Absorption spectrophotometry	Hesse (1971)
Available S	0.15% $CaCl_2$ extraction and turbidimetry	Tabatabai,1982; Massoumi and Cornfield (1963)
Available Fe, Mn, Zn, Cu	0.1M HCl extraction and Atomic Absorption Spectrophotometry	Sims and Johnson (1991)
Available B	Hot water extraction and spectrophotometry(Azomethane-H method)	Gupta (1967)
Biological properties		
Dehydrogenase activity	Reduction of 3 % TTC to methanol soluble formazon (TPF) and estimation using spectrophotometry	Lenhard (1956)

3.2.4 Weather Parameters

The mean air temperature of the location ranged from 22.64 ^{0}C to 35.29 ^{0}C and relative humidity from 79.35 - 87 per cent during the crop growth period. A total rainfall of 1748.83 mm was received which ranged from 0.40 to 463.30 mm in different months. The weather parameters during the cropping season were monitored and are presented in Fig. 1 and Appendix I.

3.2.5 Soil

The soil of the experimental site was classified as Loamy, Kaolinitic, Isohyperthermic, Typic Kandiustults belonging to Vellayani series. The fertility status of the soil is outlined along with the results (Table 10).

3.2.6 Design and Layout of the Experiment

Crop : Banana
Variety : *Nendran*
Design : RBD
Treatments : 11
Replications : 3
Plot size : 6 m x 4 m
Spacing : 2 m x 2 m

3.2.7 Treatments

Treatment combinations were imposed in the field experiment with a view to study the possibility of effecting a reduction in the recommended fertiliser dosage as per package of practices (KAU, 2016) by admixing biochar with graded levels of inorganic fertilisers. Since biochar too contributes to the soil available nutrient pool to a certain extent in the long run, a graded level of STBR inorganic fertilisers (75%) admixed with biochar was also included in the treatment combination. The treatment combinations of the field experiment are given in Table 3 and the lay out of the experimental field is depicted in Fig 2. Observations were taken from two plants in each plot.

Table 3. Treatment combinations of field experiment

No.	Treatments	Dosage
T_1	Package of practices recommendation	$\text{FYM}_{10\text{ kg}} + \text{N}_{190\text{g}} + \text{P}_{115\text{ g}} + \text{K}_{450\text{ g}} + \text{Lime}_{1000\text{ g}}$
T_2	BC @ 5 kg plant^{-1} + NPK as per POP	$\text{BC}_{5\text{ kg}} + \text{N}_{190\text{g}} + \text{P}_{115\text{ g}} + \text{K}_{450\text{ g}} + \text{Lime}_{1000\text{ g}}$
T_3	BC @ 10 kg plant^{-1} + NPK as per POP	$\text{BC}_{10\text{ kg}} + \text{N}_{190\text{g}} + \text{P}_{115\text{ g}} + \text{K}_{450\text{ g}} + \text{Lime}_{1000\text{ g}}$
T_4	BC @ 5 kg plant^{-1} + 75% NPK as per POP	$\text{BC}_{5\text{ kg}} + \text{N}_{142.50\text{g}} + \text{P}_{86.25\text{ g}} + \text{K}_{337\text{ g}} + \text{Lime}_{750\text{ g}}$
T_5	BC @ 10 kg plant^{-1} + 75% NPK as per POP	$\text{BC}_{10\text{ kg}} + \text{N}_{142.50\text{g}} + \text{P}_{86.25\text{ g}} + \text{K}_{337\text{ g}} + \text{Lime}_{750\text{ g}}$
T_6	FYM 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	$\text{FYM}_{10\text{ kg}} + \text{N}_{135\text{g}} + \text{K}_{423\text{ g}} + \text{MgSO}_{4\ 31.25\text{ g}}$
T_7	BC @ 5 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	$\text{BC}_{5\text{ kg}} + \text{N}_{135\text{g}} + \text{K}_{423\text{ g}} + \text{MgSO}_{4\ 31.25\text{ g}}$
T_8	BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	$\text{BC}_{10\text{ kg}} + \text{N}_{135\text{g}} + \text{K}_{423\text{ g}} + \text{MgSO}_{4\ 31.25\text{ g}}$
T_9	BC @ 5 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	$\text{BC}_{5\text{ kg}} + \text{N}_{101.25\text{g}} + \text{K}_{317.25\text{ g}} + \text{MgSO}_{4\ 23.44\text{ g}}$
T_{10}	BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	$\text{BC}_{10\text{ kg}} + \text{N}_{101.25\text{g}} + \text{K}_{317.25\text{ g}} + \text{MgSO}_{4\ 23.44\text{ g}}$
T_{11}	BC alone 10 kg plant^{-1}	$\text{BC}_{10\text{ kg}}$

*BC-Biochar, FYM-Farm yard manure, STBR-Soil test based recommendation

3.2.8 Crop Growth and Yield Characters

Crop growth characters were recorded from the observation plants at 2 MAP, 4 MAP, 6 MAP and 8 MAP stages of crop growth.

3.2.8.1. Plant Height

The height of the plant from the base of the pseudostem at the soil level up to the axil of the youngest unopened leaf was measured and expressed in cm.

3.2.8.2 Girth of Pseudostem

Girth of the pseudostem was taken at 20 cm above the ground level by measuring the circumference of the pseudostem and expressed in cm.

3.2.8.3 Number of Leaves per Plant

The total number of fully opened functional leaves per plant were counted and recorded.

3.2.8.4 Total Dry Matter Production

The fresh weight of pseudostem, leaves, fruits and rhizome were recorded at harvest. Samples of these parts were separately oven dried at 65 °C till it attained constant dry weight and was expressed in kg ha^{-1}.

3.2.9 Yield and Yield Attributes

Bunches were harvested at full maturity as indicated by the disappearance of angles from fingers (Stover and Simmonds, 1987). The following observations were made on the bunch characters from the observation plants.

3.2.9.1 Bunch Characters

3.2.9.1.1 Bunch Weight

Weight of the bunch including the portion of the peduncle up to the first scar (exposed outside the plant) was recorded in kg.

3.2.9.1.2 Hands Bunch^{-1}

Total number of hands in each bunch of the observation plant was counted and recorded.

3.2.9.1.3 Fingers Bunch^{-1}

The total number of fingers in each bunch of the observation plant was counted and recorded.

3.2.9.1.4 Girth of Index Finger

The girth measurement of the index finger at the mid portion was recorded using a thread and scale and expressed in cm.

3.2.9.1.5 Length of Index Finger

Length was measured from the tip of the index finger to the point of attachment of the peduncle using a thread and scale and expressed in cm.

3.2.10 Incidence of Pest and Disease

Incidence of any pest and diseases were regularly monitored and recorded from planting to crop harvest.

3.2.11 Soil Analysis

Soil samples were drawn initially and at final harvest and analysed for physical, chemical and biological properties as per standard procedures for various parameters outlined in Table 2. Soil sample were collected at 3rd and 6th month after planting and analysed for available N, P, K, Ca, Mg, S, Zn, Cu and B.

3.2.12 Nutrient Use Efficiency

Nutrient use efficiency in terms of yield was calculated by using the formula.

$$\text{NUE (\%)} = \frac{\text{Yield of treatment with biochar} - \text{Yield of treatment without biochar (POP)}}{\text{Yield of treatment without biochar (POP)}} \times 100$$

3.2.13 Total Nutrient Concentration

For banana the index plant part, midrib of third leaf was collected at harvest stage and analysed for the nutrients concentration. Analytical methods followed are outlined in Table 4.

Table 4. Analytical methods of foliar nutrient analysis

Nutrient	Method	Reference
N	Microkjeldahl distillation after digestion in H_2SO_4	Jackson (1973)
P	Nitric-perchloric (9:4) acid digestion and spectrophotometry using vanado-molybdo yellow colour method	Jackson (1973)
K	Nitric-perchloric (9:4) acid digestion and flame photometry	Jackson (1973)
Ca, Mg	Nitric-perchloric (9:4) acid digestion and atomic absorption spectrophotometry	Piper (1967)
S	Nitric-perchloric (9:4) acid digestion and Turbidimetry	Chesnin and Yien (1950)
Fe, Mn, Zn, Cu	Nitric-perchloric (9:4) acid digestion and atomic absorption spectrophotometry	Jackson (1973)
B	Dry ashing and extraction with 0.36 N H_2SO_4 and Azomethane H spectrophotometry	Bingham (1982)

3.2.14 Fruit Quality Parameters

The fully ripe index finger selected for recording the observations was used for quality analysis. Portions from the top, middle and bottom of the sample fruit were macerated in a mortar and pestle and samples drawn for analysis of quality parameters

3.2.14.1 Total Soluble Solids

The total soluble solids (TSS) was estimated using a hand refractometer and expressed in degree brix (^{0} B).

3.2.14.2 Ascorbic Acid

The ascorbic acid content of the fruits was estimated as per the method developed by Ranganna (1977) and expressed in mg 100 g^{-1} of fresh fruit sample.

3.2.14.3 Shelf Life at Ambient Conditions

The number of days taken from harvest to the development of black spots on the peel was recorded to determine the shelf life or keeping quality of fruits at room temperature (Stover and Simmonds, 1987).

3.2.15 Economic Analysis

3.2.15.1 Cost of Cultivation

Cost of cultivation under different treatments were calculated and expressed in Rs ha^{-1} and is presented in Appendix II.

3.2.15.2 Gross income

Gross income was calculated on the basis of market price of the produce and expressed in Rs ha^{-1}.

3.2.15.3 Net Income

Net income was calculated by subtracting cost of cultivation from gross income and is expressed in Rs ha^{-1}.

3.2.15.4 Benefit Cost Ratio (BCR)

BCR was worked out as the ratio of gross income to cost of cultivation

$$\text{BCR} = \frac{\text{Gross income (Rs ha}^{-1}\text{)}}{\text{Cost of cultivation (Rs ha}^{-1}\text{)}}$$

3.2.16 Statistical Analysis

The data obtained from the field experiment was analysed statistically by applying the techniques of analysis of variance (Gomez and Gomez, 1984). The F values for treatments were compared with the table values. If the effects were significant, critical differences at the 5 % significance level were calculated for effecting comparison among the means. Data analytical package Web Agri Stat Package (WASP) ver 2.0 was used for data analysis. For the data on characterisation studies, the means and standard deviations were calculated. The correlation between available nutrients in soil and yield attributes were worked out with yield.

Plate 1. A view of the experiment field

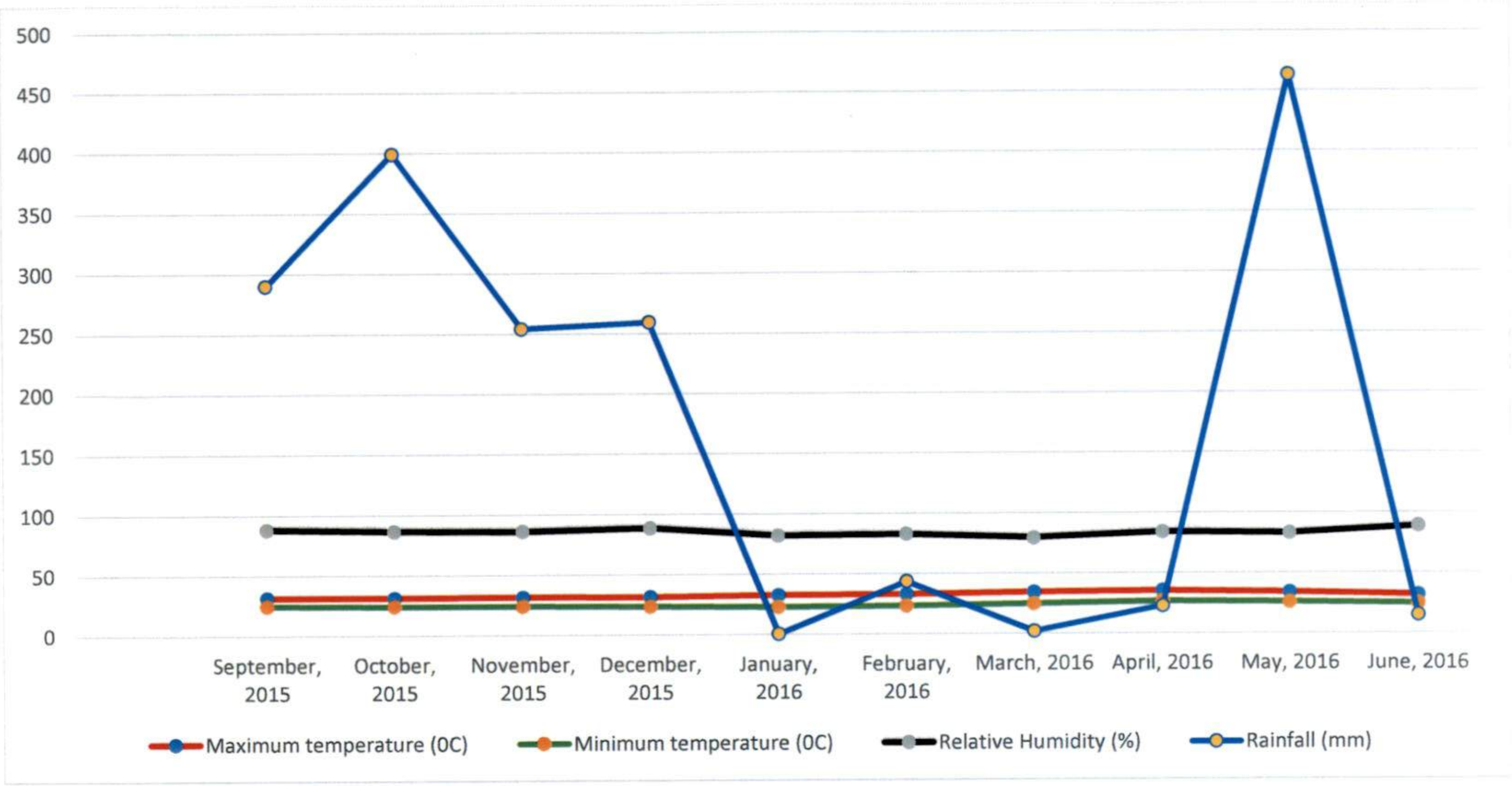
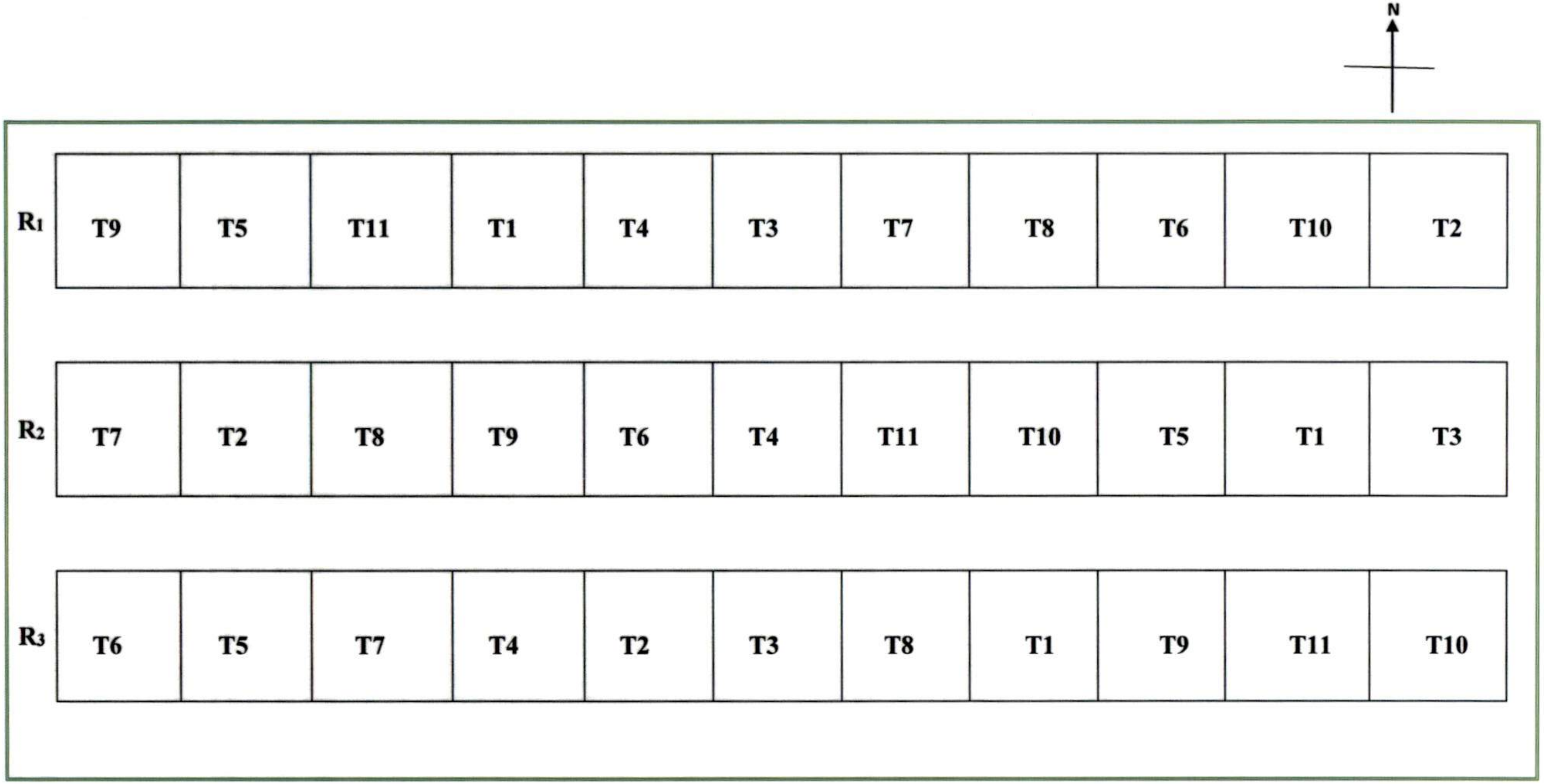


Fig. 1. Weather parameters during the growth period of banana crop



R₁	T9	T5	T11	T1	T4	T3	T7	T8	T6	T10	T2
R₂	T7	T2	T8	T9	T6	T4	T11	T10	T5	T1	T3
R₃	T6	T5	T7	T4	T2	T3	T8	T1	T9	T11	T10

Fig 2. Lay out of experiment field

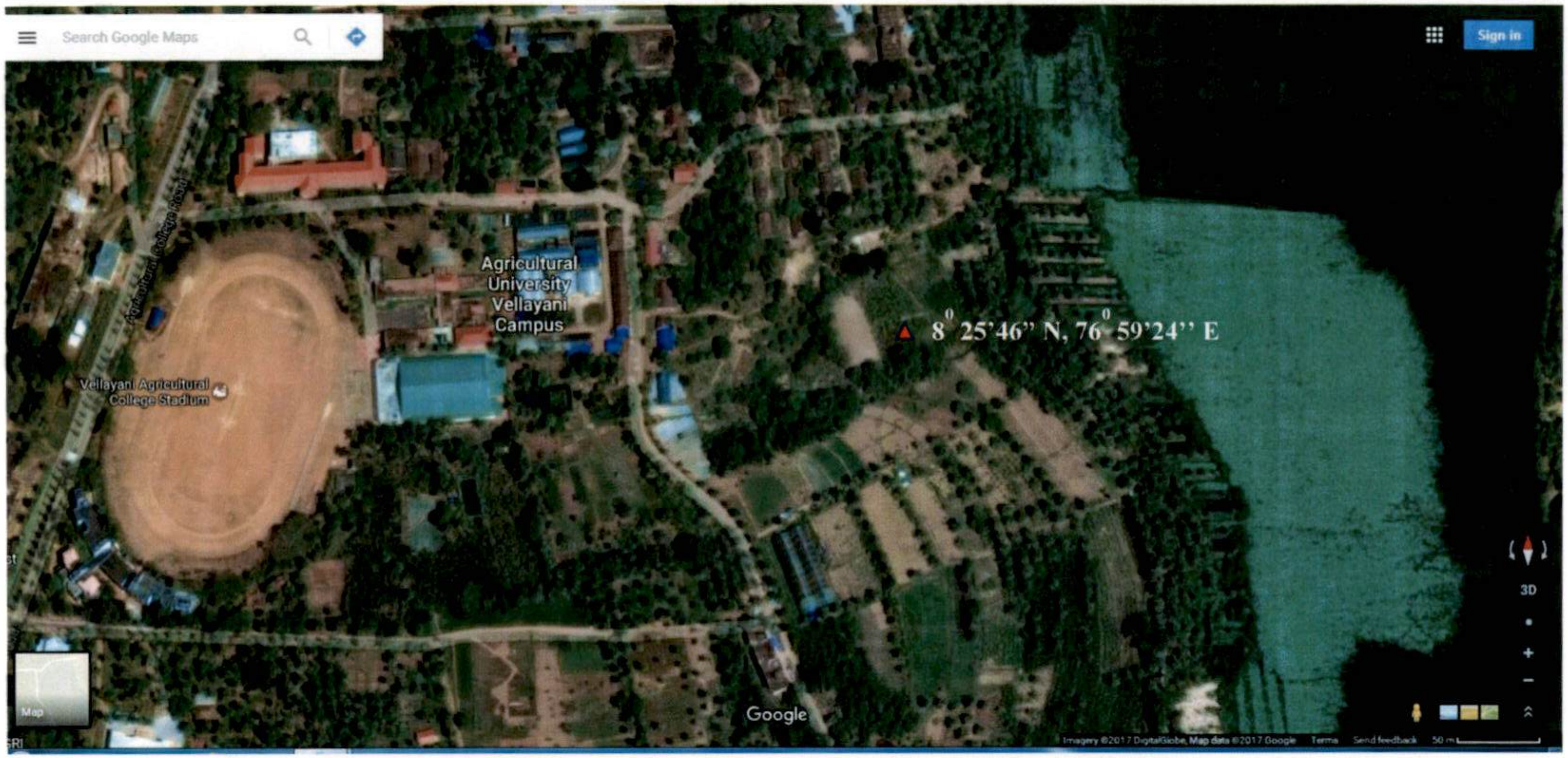


Plate 2. Imagery of the location of the experiment site

RESULTS

4. RESULTS

Biochar production from bio-waste is the best way of recycling organic waste due to its long term carbon sequestration capacity and its ability to improve crop productivity. Hence a study was done to refine the technology for micro level biochar production from tender coconut husk and evaluation of its effect on soil health, yield and quality of banana (*Musa* spp.). The results of the experiments conducted are presented in this chapter.

4.1 REFINEMENT OF BIOCHAR PRODUCTION TECHNOLOGY

The existing biochar production furnace consists of a single barrel reactor with chimney for syngas exhaustion (Dainy, 2015) (Plate 3). In order to increase the biochar production efficiency and its quality from tender coconut husk by the process of pyrolysis, a modified micro biochar kiln was conceptualised, designed and fabricated with digital temperature measuring probe and facility for syngas condensation and collection. Pyrolytic synthesis and chemical characterisation of the biochar produced from dried tender coconut husk are presented in Tables 7-10 and Plates 4-10.

4.1.1 Design and Fabrication of Modified Micro Biochar Kiln

A micro biochar kiln was developed and consists of two major components *viz.*, the basic reactor unit that provides for placement of the substrate biomass and furnace for pyrolysis, and the collection of syngas, the by-product evolved (Plate 4).

4.1.1.1 Reactor unit of the micro biochar kiln

The reactor unit of the micro biochar kiln basically consists of two GI (3 mm gauge) barrels.

a. A larger outer barrel (1.40 x 0.90 m) with lid
b. A smaller inner barrel (1.15 x 0.70 m) with lid.

The larger barrel was designed to hold the fuel material for incineration and provide for seating of the smaller biomass barrel. The larger barrel of the micro biochar kiln (1.40 m height and 0.90 m diameter) was designed with the twin objective of housing the inner biomass barrel and to serve as a furnace for incineration of fuel. A square shaped fuel slot of (0.18 x 0.18 m) was provided on the barrel at a height of 0.01 m from the base (Plate 5d). 14 number of square shaped partial aeration holes of size 0.06 x 0.06 m were provided radially at the bottom portion of the barrel. The holes were provided at height of 0.05 m and the rest 7 were provided a height of 0.16 m above the bottom of the barrel on shown in Plate 5c. The fuel slot allow a semi-continuous feed of fuel for incineration and transmit the heat to the micro kiln reactor for maintaining a continuous the pyrolytic process. Dried plant parts and agricultural waste were used for incineration in the furnace in the present experiment. Small slender pieces of iron support were fixed at the bottom of the larger barrel in order to facilitate an elevated placement of the smaller inner barrel, at a height of 0.25 m (Plate 5e). The space thus created at the bottom of the larger barrel would serve as the furnace where fuel incineration could be done.

The smaller barrel with detachable lid was designed to hold the biomass, the substrate for pyrolytic synthesis. Perforations were provided at the bottom and lid portions of the smaller barrel for enabling partial aeration during the pyrolytic process as shown in Plate 6b and 6c. Three handles were attached to the sides of the barrel for easy handling. The lid was used to cover the barrel after filling with biomass. It has a locking mechanism so as to prevent the dry tender coconut biomass substrate from spilling out of the barrel during pyrolysis.

An orifice of 0.5 cm diameter in the casing of the inner biomass barrel and another (0.08 x 0.08 m) on the casing of the outer fuel barrel were drilled with a lid to close the hole whenever not in use. This was done for facilitating measurement of the internal temperature using an infrared digital thermometer as the pyrolysis progresses inside the micro biochar kiln. (Plate 6).

61

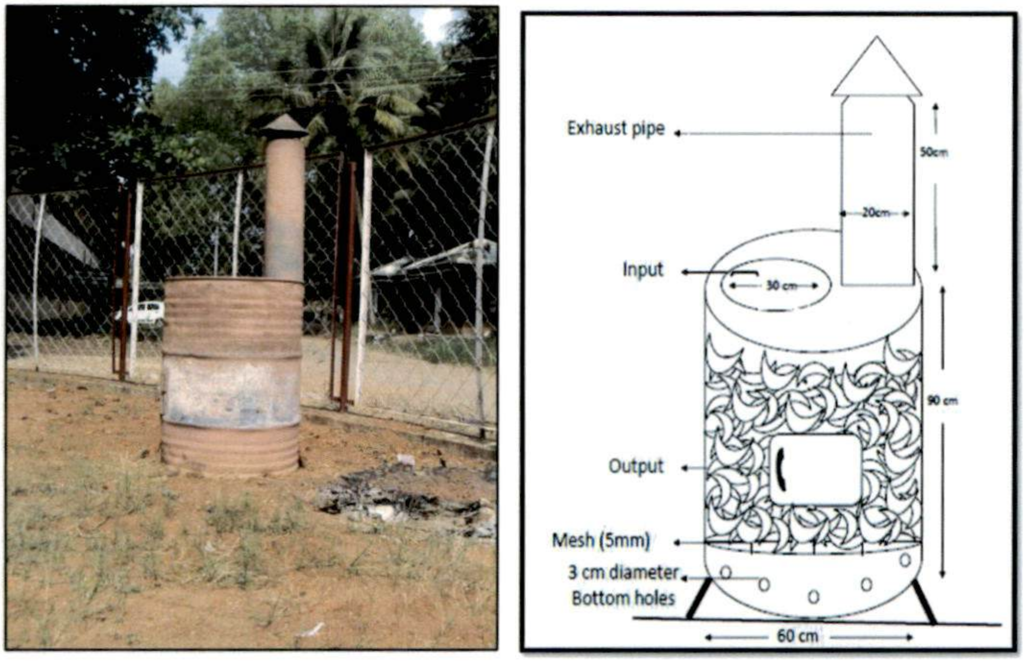


Plate 3. Previous model biochar kiln (Dainy. 2015)

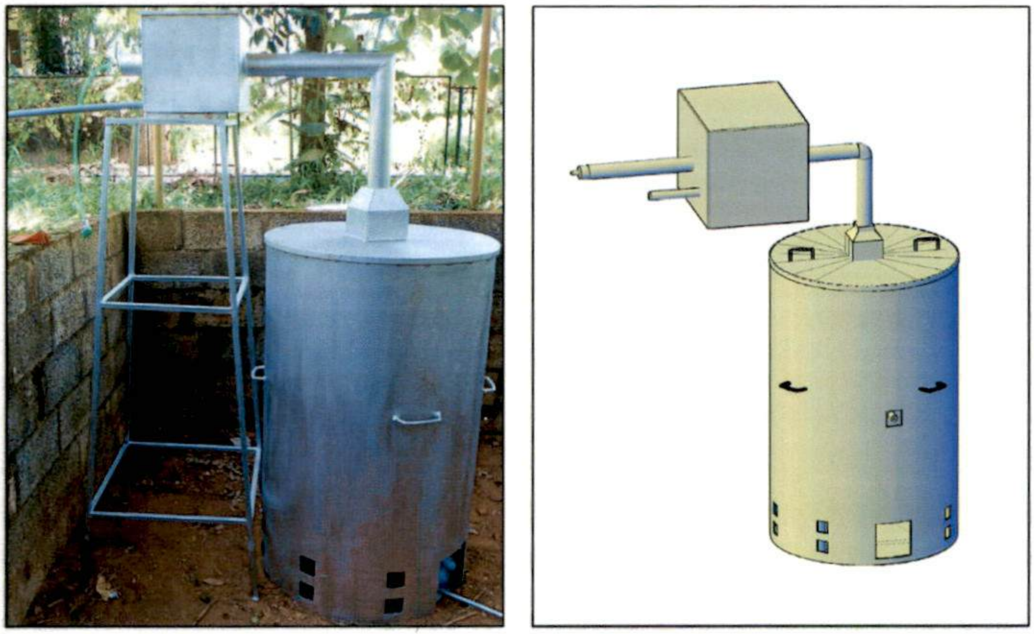
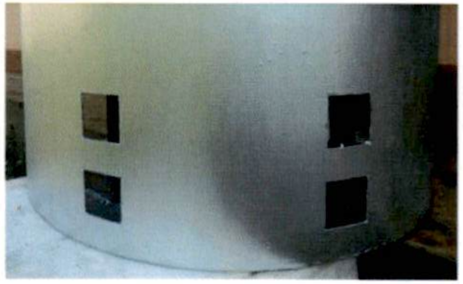


Plate 4. Modified micro biochar kiln

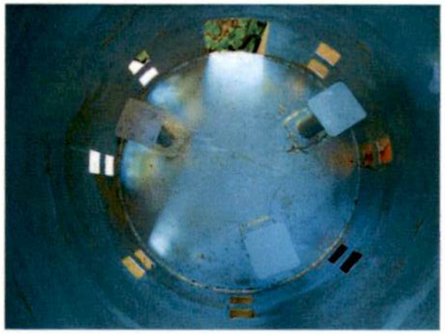
5a. Larger outer barrel

5b. Outer barrel lid with chimney



5c. Holes for partial aeration

5d. Firewood fuel slot



5e. Iron pegs fixed on the inside of the larger barrel

Plate 5. Outer barrel of the double barrel reactor unit of the prototype micro biochar kiln

6a. Inner biomass barrel

6b. Lid with small holes for aeration

6c. Small holes at the bottom of the biomass barrel

6d. Lid secured tightly with lock

6e. Orifice for temperature measurement

6f. Monitoring temperature with digital infrared thermometer

Plate 6. Inner biomass barrel of the double barrel reactor unit of the prototype micro biochar kiln

7a. Cooling chamber

7b. Flow of condensed syngas

7c. Tedler bag for collecting syngas

Plate 7. Cooling assembly for condensation, saturation and collection of syngas

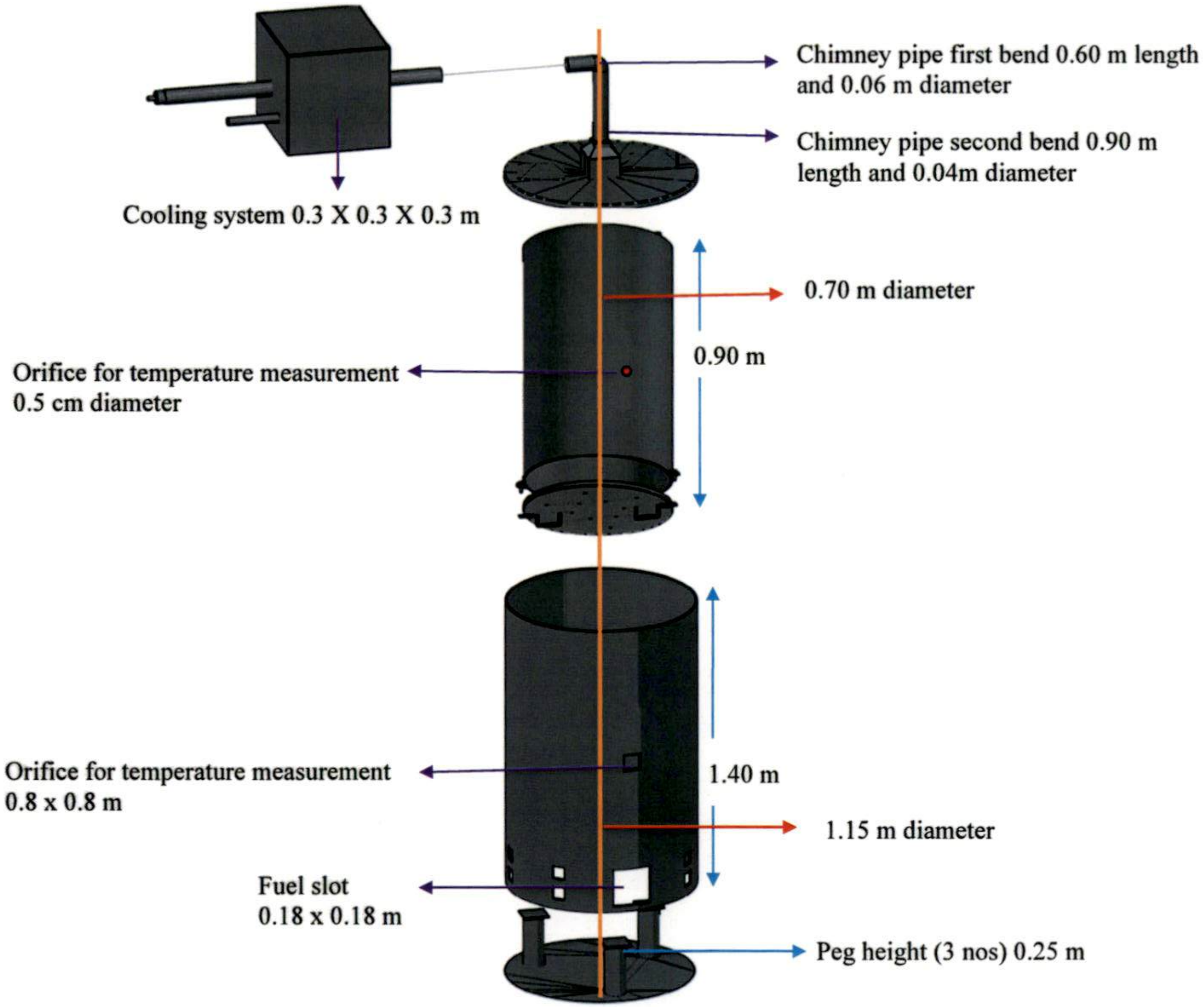


Plate 8. Parts of the indigenously designed and fabricated prototype of micro biochar kiln

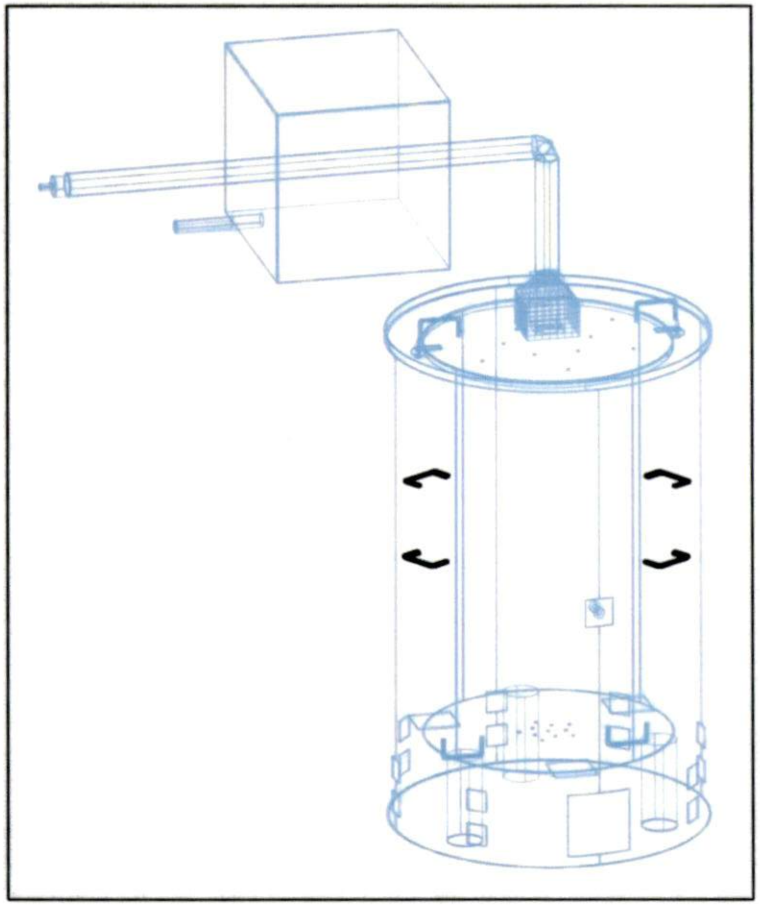


Plate 9. Schematic diagram showing placement of smaller biomass barrel inside the larger barrel

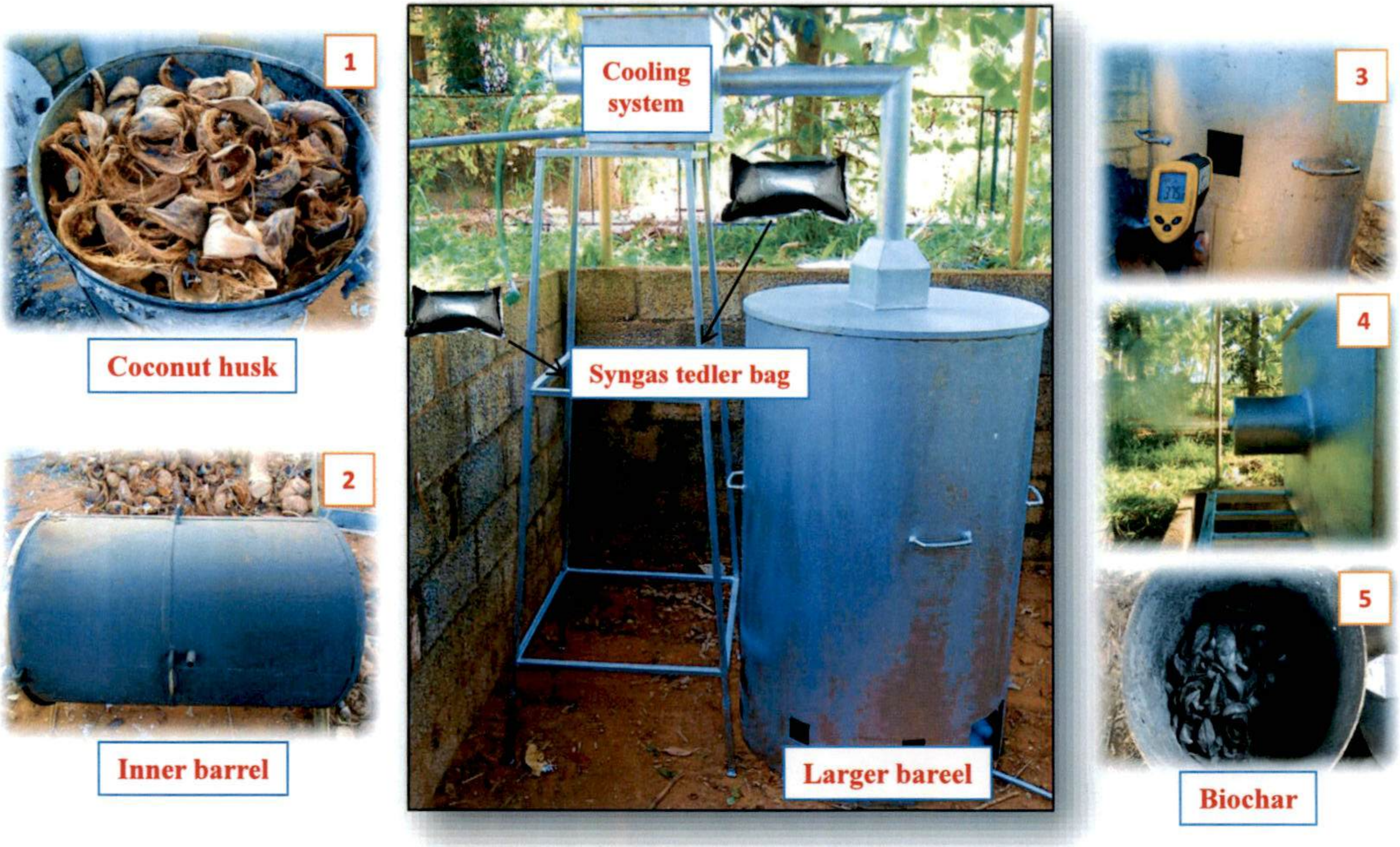
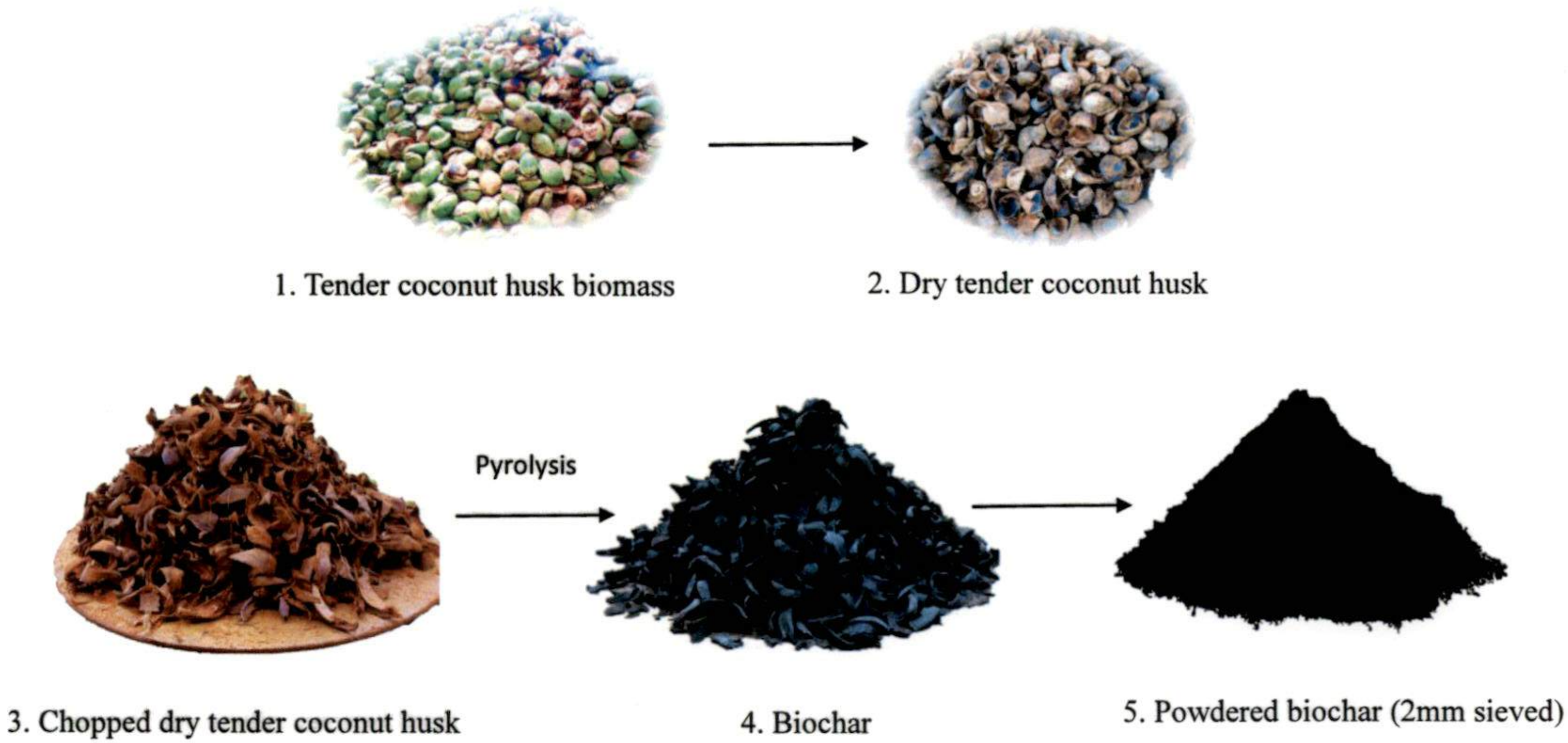


Plate 10. Steps in pyrolytic production of biochar in the micro kiln



1. Tender coconut husk biomass

2. Dry tender coconut husk

3. Chopped dry tender coconut husk

4. Biochar

5. Powdered biochar (2mm sieved)

Plate 11. A flow chart showing biochar production from tender coconut husk

4.1.1.2 Collection of Syngas

A cooling assembly unit was also designed to facilitate the collection of syngas, the by-product produced during the pyrolytic conversion of biomass to biochar. The lid of the larger barrel was modified by cutting a small hole at its centre with a diameter of 0.06 m for enabling attachment of the chimney pipe to the lid. The chimney pipe can be inserted and coupled with the lid. This pipe has 2 bends, the first bend at 0.60 m with 0.06 m diameter and the second bend at 0.90 m with 0.04 m diameter (Plate 7).

The distal end of the chimney pipe is connected to the cooling chamber. The water inside the cooling chamber helps for the condensation and saturation of the syngas, the major by product released during the pyrolytic process. The condensed and saturated syngas that comes out of the pipe can be collected in tedler bags.

4.1.2 Biochar Production from Tender Coconut Husk Biomass

Dry tender coconut husk (30 kg) was taken in the smaller biomass barrel of the micro kiln unit and the lid was placed over the barrel. The smaller barrel was turned upside down, and inserted into the larger barrel, such that it rested on the pegs placed 0.25 m above the base of the outer larger barrel. Fuel material was inserted into the fuel slot of the furnace and incinerated (Plate 9).

The small holes drilled in the bottom sides of the outer barrel permits free air flow through the space between the barrels, which would favour the combustion reaction occurring therein. Furthermore, the chimney was placed over the outer barrel in order to create an updraft of air. The configuration was such that the burning fuel at the bottom of the large barrel would heat up the walls of the biomass barrel, which in turn transmits and heat up the tender coconut husk waste placed inside this biomass barrel. When the biomass substrate attained a temperature above 350 °C at about 30 minutes, the process of pyrolysis started. The periodicity of temperature build-up of the micro kiln leading to slow pyrolysis is presented in Table 5. The temperature build-up during pyrolysis biomass substrate was

70

monitored using the digital infrared thermometer. It took 90 minutes for the completion of the pyrolytic process. The syngas released by this process was forced out of the inner biomass barrel and passed through the cooling assembly and collected in tedler bags (Plate 10).

At the end of the pyrolytic process, the kiln is allowed to cool down for a short period of time. After cooling, inner barrel taken out and collected the biochar produced. 30 kg dry tender coconut husk biomass yielded 15 kg biochar. The recovery percentage was 50 %. Biochar produced was crushed with a wooden pestle and sieved through a 2 mm sieve and stored in containers.

4.1.1 Biochar Characterization

Biochar produced was analysed for electrochemical and chemical properties presented in Table 7 and 8. Biochar from tender coconut husk had an alkaline pH (8.53), high total organic carbon (70.10 %), CEC (15.26 cmol kg^{-1}) and AEC (5.64 cmol kg^{-1}). Nutrient composition of the biochar revealed that it had N (1.52 %), P (0.40 %), K (2.26 %), Ca (0.54 %), Mg (0.46 %), S (0.27 %), Fe (89.9 mg kg^{-1}), Mn (2.84 mg kg^{-1}) and B (6.78 mg kg^{-1}). C:N, C:P, C:S and C:N:P:S ratios were 46.11, 175.25, 259.62 and 350:7.5:2:1 respectively. The heavy metal contents (Pb, Cd, Ni, Cr, Zn and Cu) were very low when compared to the maximum allowed threshold levels. Biochar from tender coconut husk chemical characteristics and heavy metal contents are presented in Tables 7 and 8.

4.1.2 Syngas Analysis

Syngas, the by-product produced during pyrolysis was analysed in a micro gas chromatograph and presented in Table 9 and Appendix III. The principal gases detected in the syngas were carbon dioxide (67.7 %), methane (22.89 %), oxygen (8.74%), hydrogen (0.66%) and n-butane (0.001%), respectively normal mol % (dry) basis.

Table 5. Temperature build up within the reactor unit of the micro biochar kiln

Time (min)	Temperature (°C)
0	37
5	118
10	180
15	210
20	220
25	300
30	>350
Above 30 – 90	-

Table 6. Specifications of the indigenously designed and fabricated micro biochar kiln

Item	Specification
Reactor unit of micro kiln	
Dimension (diameter, height) of the smaller biomass barrel	0.90 X 0.70 m
Dimension (diameter, height) of the larger fuel barrel	1.40 X 1.15 m
Peg height (3 nos)	0.25m
Input capacity of biomass (tender coconut husk, dried, chopped)	30 kg
Output (biochar)	15 kg
Recovery percentage of biochar	50 %
Orifice for temperature measurement (biomass barrel)	0.5 cm diameter
Orifice for temperature measurement (outer barrel)	0.8 X 0.8 m^2
Cooling assembly of micro kiln	
Dimension (length, diameter) of chimney pipe (first bend)	0.60 m with 0.06 m diameter
Dimension (length, diameter) of chimney pipe (second bend)	0.90 m with 0.04 m diameter
Cooling chamber	0.3 x 0.3 x 0.3 m
Height of ladder supporting cooling unit	1.7 m

Table 7. Electro-chemical and chemical characteristics of biochar from tender coconut husk

Parameter	Biochar
pH (1:20)	8.53 ± 0.13
EC (1:20) (dS m^{-1} at 25°C)	1.70 ± 0.02
CEC (cmol kg^{-1})	15.26 ± 0.64
AEC (cmol kg^{-1})	5.64 ± 0.23
TOC (%)	70.10 ± 1.82
N (%)	1.52 ± 0.85
P (%)	0.40 ± 0.10
K (%)	2.26 ± 0.05
Ca (%)	0.54 ± 0.07
Mg (%)	0.46 ± 0.07
S (%)	0.27 ± 0.03
Fe (mg kg^{-1})	89.90 ± 0.99
Mn (mg kg^{-1})	2.84 ± 0.66
B (mg kg^{-1})	6.78 ± 1.83
C:N	46.11
C:P	175.25
C:S	259.62
C:N:P:S	350:7.5:2:1

Table 8. Heavy metal content in biochar from tender coconut husk, $mgkg^{-1}$

Heavy metal	Biochar	Maximum Allowed Thresholds (IBI, 2014)
Pb	0.18 ± 0.18	212-300
Cd	0.03 ± 0.02	1.9-39
Ni	0.02 ± 0.01	47-420
Cr	0.06 ± 0.02	93-1200
Zn	6.18 ± 1.08	416-7400
Cu	0.51 ± 0.04	143-6000

73

Table 9. Composition of syngas produced during pyrolysis of tender coconut husk

Component name	Ret. time	Peak area	Raw amount	Norm mol % (dry)	Norm mol % (sat.)	Weight % (dry)	Weight % (sat.)
Methane	0.466	11315171.0	20.4700	22.8943	22.5091	10.1241	10.0388
Ethane	0.491	0.0	0.0000	0.0000	0.0000	0.0000	0.0000
Propane	0.858	0.0	0.0000	0.0000	0.0000	0.0000	0.0000
n-Butane	0.376	1011.0	0.0010	0.0011	0.0011	0.0018	0.0018
Nitrogen	0.300	0.0	0.0000	0.0000	0.0000	0.0000	0.0000
Carbon Dioxide	0.382	38471426.0	60.5330	67.7020	66.5627	82.1281	81.4360
Water	0.000	0.0	0.0000	0.0000	1.6827	0.0000	0.8427
Hydrogen	0.365	1444640.0	0.5920	0.6621	0.6510	0.0368	0.0365
Carbon Monoxide	1.516	0.0	0.0000	0.0000	0.0000	0.0000	0.0000
Helium	0.340	0.0	0.0000	0.0000	0.0000	0.0000	0.0000
Neon	3.667	0.0	0.0000	0.0000	0.0000	0.0000	0.0000
Oxygen	0.432	2501963.0	7.8150	8.7405	8.5934	7.7092	7.6442
Ethylene	0.469	0.0	0.0000	0.0000	0.0000	0.0000	0.0000
Acetylene	0.516	0.0	0.0000	0.0000	0.0000	0.0000	0.0000
n-Hexane	1.095	0.0	0.0000	0.0000	0.0000	0.0000	0.0000
n-Heptane	2.201	0.0	0.0000	0.0000	0.0000	0.0000	0.0000
Methyl Acetylene	0.298	0.0	0.0000	0.0000	0.0000	0.0000	0.0000
Total			89.4110	100.0000	100.0000	100.0000	100.0000

4.2 FIELD EXPERIMENT FOR EVALUATION OF BIOCHAR ON SOIL HEALTH, YIELD AND QUALITY OF BANANA

4.2.1 Assessment of Soil Fertility Status of Experimental Area

The soil test results of the representative sample from the experimental area is furnished in Table 10. The soil was acidic in reaction, medium in organic carbon content (1.13 ± 0.08 %), available N and K. The available P content was very high in the experiment site. Among the secondary nutrients, Ca and S were sufficient and Mg alone was deficient (47.34 ± 5.14 mg kg^{-1}). Fe, Mn, Zn, Cu and B were found to be in sufficient range.

4.2.2 Soil Test Based Fertilizer Recommendation for Nendran Banana

The inorganic nutrient content required as per the package of practices recommendation and the computed soil test based nutrient recommendation for Nendran banana are presented in Table 11. Biochar synthesized from tender coconut husk was applied as basal @ 5 kg plant^{-1} or 10 kg plant^{-1} in accordance with the treatments.

4.2.3 Growth Characters of Banana as Influenced by Biochar Based Treatments

The results of the bimonthly observations on the plant biometric characters plant height, girth of pseudostem and number of leaves per plant are presented in Tables 12-14.

4.2.3.1 Plant Height

Observations taken on the mean plant height of banana at 2, 4, 6 and 8 MAP are furnished in Table12. The biochar based treatments recorded the highest plant height at all stages. The BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T_{10}) treatment recorded the highest plant height of 104.33 cm, 212.66 cm, 288.66 cm and 328.66 cm at 2, 4, 6 and 8 MAP, followed by BC @ 5 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR)

(T_9) which scored 93 cm, 190 cm, 266 cm and 296 cm at different stages. Lowest plant height was recorded by the BC alone 10 kg plant^{-1} (T_{11}) treatment at all stages.

Table 10. Soil fertility parameters of experimental site

Fertility parameters	Content	Status
Mechanical properties		
Sand (%)	74.24	Sandy clay loam
Silt	4.00	
Clay	21.76	
Physical properties		
Bulk density (Mg m^{-3})	1.37 ± 0.03	-
Porosity (%)	47.05 ± 1.99	-
WHC (%)	28.28 ± 1.02	-
Chemical properties		
pH	4.73 ± 0.04	Very strongly acid
EC (dS m^{-1} at 25°C)	0.71 ± 0.09	-
CEC (cmol kg^{-1})	3.36 ± 0.06	Low
OC %	1.13 ± 0.08	Medium
N (kg ha^{-1})	225.57 ±12.42	Medium
P (kg ha^{-1})	80.40 ± 8.11	High
K(kg ha^{-1})	130.20 ± 23.99	Medium
Ca (mg kg^{-1})	374.90 ± 36.22	Sufficient
Mg (mg kg^{-1})	47.34 ± 5.14	Deficient
S (mg kg^{-1})	50.68 ± 10.15	Sufficient
Fe (mg kg^{-1})	26.19 ± 7.35	Sufficient
Mn(mg kg^{-1})	6.42 ± 3.18	Sufficient
Zn (mg kg^{-1})	2.99 ± 0.08	Sufficient
Cu (mg kg^{-1})	4.70 ± 2.83	Sufficient
B (mg kg^{-1})	1.71 ± 0.07	Sufficient
Biological properties		
Dehydrogenase activity (μg TPF g^{-1} soil 24 h^{-1})	38.62	-

Table 11. Fertilizer requirement for different treatments for banana

Nutrient (g plant^{-1})	POP	POP (75 %)	STBR	STBR (75 %)	Inorganic nutrient Source
N	190.00	142.50	159.60	119.70	Urea
P	115.00	86.25	-	-	Rock phosphate
K	450.00	337.50	423.00	317.25	Muriate of potash
Ca	1000.00	750.00	-	-	Lime
Mg	-	-	31.25	23.44	Magnesium sulphate

4.2.3.2 Girth of Pseudostem

It is evident from Table 13 that the girth of pseudostem at the base is significantly influenced by the treatments at all stages of sampling. The BC @ 5 kg plant^{-1} + 75% NPK as per POP (T_4) treatment recorded the maximum pseudostem girth of 57.33 cm at 6 MAP. At 4 and 8 MAP stages BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T_{10}) registered the maximum girths of 56.16 cm and 58.33 cm respectively, which was on par with BC @ 5 kg plant^{-1} + 75 % NPK as per POP (T_4), BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR) (T_8) and BC @ 5 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR) (T_7) treatments at 4, 8 MAP stages. All the stages BC alone 10 kg plant^{-1} (T_{11}) recorded lowest girth of pseudostem.

4.2.3.3 Mean Number of Leaves per Plant

Data on the total number of leaves per plant revealed the superiority of biochar treatment at all stages of observation (Table 14). The highest mean number of leaves of 12.66 in the entire experiment was registered at 4 MAP by BC @ 5 kg plant^{-1} + NPK as per POP (T_4) treatment which was on par with BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR) (T_8) treatment. At 2 and 6 MAP, BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T_{10}) recorded highest number of leaves of 9.33, 11.33 respectively. At 2, 4 and 6 MAP stages BC alone 10 kg plant^{-1} (T_{11}) recorded the lowest number of leaves, 7.33, 9.66 and 9.33 respectively.

77

4.2.4 Dry Matter Production in Banana as Influenced by Biochar Treatments

The various treatments exhibited significant statistical variations in the total dry matter produced as well as in its constituent plant parts of leaf, rhizome, pseudostem and fruit as is evident in Table 15. The highest dry matter production of 12742.15 kg ha^{-1} was recorded in the BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T_{10}) treatment which was on par with the BC @ 5 kg plant^{-1} + 75% NPK as per POP (T_4) treatment. Total dry matter production among all treatments followed the order $T_{10} > T_4 > T_6 > T_9 > T_2 > T_8 > T_5 > T_7 > T_3 > T_1 > T_{11}$.

Highest leaf, rhizome and fruit dry matter production was recorded by the BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T_{10}) treatment with values of 2741.66, 2654.16 and 3645.75 kg ha^{-1} respectively. The pseudostem weight of BC @ 5 kg plant^{-1} + 75% NPK as per POP (T_4) treatment was high compared to all other treatments except T_8, T_7, T_3, T_1 and T_{11} treatments. Lowest contribution of leaf, pseudostem, rhizome and fruit weight to the total dry matter production, 1465.38, 1650.45, 1437.50 and 2360.68 kg ha^{-1} was observed in BC alone 10 kg plant^{-1} (T_{11}) treatment.

4.2.5 Yield and Yield Attributes in Banana as Influenced by Biochar Based Treatments

The bunch yield and various yield attributes of banana with regard to different biochar based treatments have been outlined in Table 16. The yield and important yield characters subjected to study reflected the superiority of the biochar based treatments. The highest bunch yield of 9.34 kg was recorded by BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T_{10}) treatment (Plate 12). The bunch yield obtained was in the following order $T_{10} > T_4 > T_9 > T_6 > T_2 > T_8 > T_3 > T_5 > T_7 > T_1 > T_{11}$.

The mean number of hands bunch^{-1} was highest (5.25) in BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T_{10}) and BC @ 5 kg plant^{-1} + NPK as per POP (T_2) and BC @ 5 kg plant^{-1} + NPK as per POP (T_4) treatments which was on par with the FYM 10 kg plant^{-1} + (NPK + secondary &

micronutrients as per STBR) (T_6) (5.15) and BC @ 5 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T_9) (5.00) treatments.

BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T_{10}) treatment registered highest number of fingers bunch^{-1} which was on par with FYM 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR) (T_6), BC @ 5 kg plant^{-1} + NPK as per POP (T_2) and BC @ 5 kg plant^{-1} + NPK as per POP (T_4) treatments recording values of 45.50, 45.33 and 44.33 respectively. BC alone 10 kg plant^{-1} (T_{11}) recorded minimum number of hands bunch^{-1} (4.00) and fingers bunch^{-1} (34.33). The BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T_{10}) treatment proved to be superior to all other treatments in terms of the length (22.83 cm) and girth (12.73 cm) of the index finger. The lowest length (18.25 cm) and girth (10.35 cm) of index finger was seen in BC alone 10 kg plant^{-1} (T_{11}) treatment (Plate 13).

4.2.6 Quality Parameters of Banana Fruit as Influenced by Biochar Based Treatments

The effect of the biochar based treatments on the fruit quality parameters of banana like total soluble solids, ascorbic acid content and shelf life of the fruits were studied and were found to be statistically significant (Table 17). The highest total soluble solid content of 34 % was observed in BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T_{10}) treatment, followed by BC @ 5 kg plant^{-1} + 75% NPK as per POP (T_4) (33.16 %). The highest ascorbic acid content of 2.18 mg 100g^{-1} was recorded by BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T_{10}) treatment. The BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T_{10}) treatment registered the highest shelf life of 9.66 days and it was on par with the BC @ 5 kg plant^{-1} + 75% NPK as per POP (T_4) and BC @ 5 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T_9) treatment. The lowest soluble solid (31.83 %) and ascorbic acid content (0.84 mg 100g^{-1}) was recorded by the BC alone 10 kg plant^{-1} (T_{11}) treatment.

Table 12. Effect of treatments on plant height of banana, cm

	2 MAP	4 MAP	6 MAP	8 MAP
T$_1$- Package of practices recommendation	76.33 ^{j}	156.66 ^{j}	232.66 ^{g}	242.66 ^{ef}
T$_2$- BC @ 5 kg plant^{-1} + NPK as per POP	82.00 ^{g}	168.00 ^{g}	244.00 ^{e}	257.33 ^{cd}
T$_3$- BC @ 10 kg plant^{-1} + NPK as per POP	79.00 ^{i}	162.00 ^{i}	238.00 ^{f}	253.66 ^{cd}
T$_4$- BC @ 5 kg plant^{-1} + 75% NPK as per POP	85.00 ^{e}	174.00 ^{e}	250.00 ^{d}	290.00 ^{b}
T$_5$- BC @ 10 kg plant^{-1} + 75% NPK as per POP	80.00 ^{h}	164.00 ^{h}	240.00 ^{f}	246.66 ^{de}
T$_6$- FYM 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	90.00 ^{c}	184.00 ^{c}	260.00 ^{c}	290.00 ^{b}
T$_7$- BC @ 5 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	83.00 ^{f}	170.00 ^{f}	246.00 ^{e}	263.33 ^{c}
T$_8$- BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	89.00 ^{d}	182.00 ^{d}	258.00 ^{c}	294.66 ^{b}
T$_9$- BC @ 5 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	93.00 ^{b}	190.00 ^{b}	266.00 ^{b}	296.00 ^{b}
T$_{10}$- BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	104.33 ^{a}	212.66 ^{a}	288.66 ^{a}	328.66 ^{a}
T$_{11}$- BC alone 10 kg plant^{-1}	75.00 ^{k}	154.00 ^{k}	227.66 ^{h}	234.33 ^{f}
SEm (±)	0.30	0.61	1.21	5.15
CD (0.05)	0.64	1.29	2.54	10.76

*BC-Biochar, FYM-Farm yard manure, STBR-Soil test based recommendation; ^{a,b,c,d,e,f} Significant difference between treatments

Table 13. Effect of treatments on pseudostem girth of banana, cm

	2 MAP	4 MAP	6 MAP	8 MAP
T$_1$- Package of practices recommendation	31.83	49.16 ^{d}	50.83 ^{e}	51.50 ^{e}
T$_2$- BC @ 5 kg plant^{-1} + NPK as per POP	32.66	52.66 ^{abcd}	51.00 ^{e}	52.33 ^{de}
T$_3$- BC @ 10 kg plant^{-1} + NPK as per POP	30.50	49.83 ^{cd}	51.66 ^{de}	52.16 ^{de}
T$_4$- BC @ 5 kg plant^{-1} + 75% NPK as per POP	33.33	53.33 ^{abc}	57.33 ^{a}	58.00 ^{a}
T$_5$- BC @ 10 kg plant^{-1} + 75% NPK as per POP	32.16	52.16 ^{bcd}	51.16 ^{e}	52.66 ^{d}
T$_6$- FYM 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	32.33	49.00 ^{d}	53.33 ^{cde}	55.00 ^{c}
T$_7$- BC @ 5 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	34.16	54.16 ^{abc}	56.16 ^{abc}	57.50 ^{a}
T$_8$- BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	34.83	54.83 ^{ab}	55.66 ^{abc}	57.33 ^{ab}
T$_9$- BC @ 5 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	33.16	53.16 ^{abc}	54.33 ^{bcd}	56.33 ^{b}
T$_{10}$- BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	36.16	56.16 ^{a}	57.00 ^{ab}	58.33 ^{a}
T$_{11}$- BC alone 10 kg plant^{-1}	32.83	42.83 ^{e}	46.83 ^{f}	48.16 ^{f}
SEm (±)	1.07	1.89	1.39	0.49
CD (0.05)	NS	3.96	2.91	1.03

*BC-Biochar, FYM-Farm yard manure, STBR-Soil test based recommendation; ^{a,b,c,d,e} Significant difference between treatments

Table 14. Effect of treatments on number of leaves of banana

	2 MAP	4 MAP	6 MAP	8 MAP
T$_1$- Package of practices recommendation	7.00 ^{c}	11.50 ^{bc}	10.83 ^{ab}	10.83
T$_2$- BC @ 5 kg plant^{-1} + NPK as per POP	8.00 ^{bc}	11.50 ^{bc}	9.66 ^{cd}	10.83
T$_3$- BC @ 10 kg plant^{-1} + NPK as per POP	8.00 ^{bc}	11.50 ^{bc}	10.16 ^{bcd}	10.83
T$_4$- BC @ 5 kg plant^{-1} + 75% NPK as per POP	9.00 ^{ab}	12.66 ^{a}	10.16 ^{bcd}	11.33
T$_5$- BC @ 10 kg plant^{-1} + 75% NPK as per POP	8.00 ^{bc}	11.50 ^{bc}	11.00 ^{ab}	10.83
T$_6$- FYM 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	8.66 ^{ab}	11.66 ^{bc}	10.66 ^{abc}	11.00
T$_7$- BC @ 5 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	8.00 ^{bc}	11.33 ^{c}	9.16 ^{d}	10.66
T$_8$- BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	8.00 ^{bc}	12.16 ^{ab}	10.16 ^{bcd}	10.83
T$_9$- BC @ 5 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	9.00 ^{ab}	11.33 ^{c}	10.83 ^{ab}	10.66
T$_{10}$- BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)`1	9.33 ^{a}	11.66 ^{bc}	11.33 ^{a}	11.00
T$_{11}$- BC alone 10 kg plant^{-1}	7.33 ^{c}	9.66 ^{d}	9.33 ^{d}	9.33
SEm (±)	0.61	0.38	0.51	0.41
CD (0.05)	1.29	0.81	1.08	NS

*BC-Biochar, FYM-Farm yard manure, STBR-Soil test based recommendation; ^{a,b,c,d} Significant difference between treatments

Table 15. Effect of treatments on dry matter production in banana, kg ha^{-1}

	Leaf	Pseudostem	Rhizome	Fruit	Total
T$_1$- Package of practices recommendation	1722.50 ^{g}	2065.05 ^{bc}	1562.50 ^{de}	2423.19 ^{d}	7773.24 ^{ef}
T$_2$- BC @ 5 kg plant^{-1} + NPK as per POP	1820.97 ^{g}	3227.03 ^{a}	2416.66 ^{ab}	3183.60 ^{bc}	10648.28 ^{bc}
T$_3$- BC @ 10 kg plant^{-1} + NPK as per POP	1733.33 ^{g}	2146.37 ^{bc}	1806.25 ^{cd}	2511.93 ^{d}	8197.88 ^{de}
T$_4$- BC @ 5 kg plant^{-1} + 75% NPK as per POP	2631.25 ^{ab}	3832.01 ^{a}	2387.50 ^{ab}	3504.20 ^{ab}	12354.96 ^{a}
T$_5$- BC @ 10 kg plant^{-1} + 75% NPK as per POP	2214.58 ^{d}	3389.72 ^{a}	1785.41 ^{cd}	2589.51 ^{d}	9979.23 ^{c}
T$_6$- FYM 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	2345.83 ^{c}	3687.40 ^{a}	1841.66 ^{c}	3341.09 ^{abc}	11216.00 ^{b}
T$_7$- BC @ 5 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	1950.00 ^{f}	2442.26 ^{b}	1945.83 ^{c}	2572.67 ^{d}	8910.77 ^{d}
T$_8$- BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	2529.16 ^{b}	2518.22 ^{b}	1833.33 ^{c}	3134.80 ^{c}	10015.52 ^{c}
T$_9$- BC @ 5 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	2091.66 ^{e}	3264.28 ^{a}	2270.83 ^{b}	3460.14 ^{abc}	11086.92 ^{b}
T$_{10}$- BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	2741.66 ^{a}	3700.56 ^{a}	2654.16 ^{a}	3645.75 ^{a}	12742.15 ^{a}
T$_{11}$- BC alone 10 kg plant^{-1}	1465.38 ^{h}	1650.45 ^{c}	1437.50 ^{e}	2360.68 ^{d}	6914.02 ^{f}
SEm (±)	57.26	332.27	127.95	157.84	467.13
CD (0.05)	119.46	693.12	266.92	329.26	974.44

*BC-Biochar, FYM-Farm yard manure, STBR-Soil test based recommendation; ^{a,b,c,d,e} Significant difference between treatments

Table 16. Effect of treatments on bunch yield and bunch characters of banana

	Weight of bunch (kg)	Number of hands bunch^{-1}	Number of fingers bunch^{-1}	Index Finger	
				Length (cm)	Girth (cm)
T$_1$- Package of practices recommendation	6.21 ^{fg}	4.25 ^{de}	36.83 ^{de}	19.08 ^{f}	11.76 ^{d}
T$_2$- BC @ 5 kg plant^{-1} + NPK as per POP	7.02 ^{cde}	5.25 ^{a}	45.33 ^{ab}	19.58 ^{ef}	12.55 ^{abc}
T$_3$- BC @ 10 kg plant^{-1} + NPK as per POP	6.90 ^{def}	5.00 ^{abc}	40.00 ^{cd}	20.54 ^{d}	12.22 ^{c}
T$_4$- BC @ 5 kg plant^{-1} + 75% NPK as per POP	8.14 ^{b}	5.25 ^{a}	44.33 ^{abc}	22.04 ^{b}	12.64 ^{ab}
T$_5$- BC @ 10 kg plant^{-1} + 75% NPK as per POP	6.83 ^{def}	4.75 ^{bc}	34.50 ^{e}	21.33 ^{bc}	12.24 ^{c}
T$_6$- FYM 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	7.35 ^{bcd}	5.15 ^{ab}	45.50 ^{a}	20.75 ^{cd}	12.66 a
T$_7$- BC @ 5 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	6.36 ^{ef}	4.75 ^{bc}	39.16 ^{d}	20.08 ^{de}	12.24 ^{c}
T$_8$- BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	7.02 ^{cde}	4.60 ^{cd}	39.50 ^{d}	20.41 ^{d}	12.30 ^{bc}
T$_9$- BC @ 5 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	7.78 ^{bc}	5.00 ^{abc}	41.00 ^{bcd}	21.66 ^{b}	12.54 ^{abc}
T$_{10}$- BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	9.34 ^{a}	5.25 ^{a}	46.16 ^{a}	22.83 ^{a}	12.73 ^{a}
T$_{11}$- BC alone 10 kg plant^{-1}	5.44 ^{g}	4.00 ^{e}	34.33 ^{e}	18.25 ^{g}	10.35 ^{e}
SEm (±)	0.37	0.20	2.10	0.36	0.15
CD (0.05)	0.79	0.42	4.40	0.76	0.33

*BC-Biochar, FYM-Farm yard manure, STBR-Soil test based recommendation; ^{a,b,c,d,e} Significant difference between treatments

Table 17. Effect of treatments on quality parameters of fruit of banana

	Total Soluble Solids (^{0} B)	Ascorbic acid (mg 100g^{-1})	Shelf life (days)
T$_1$- Package of practices recommendation	32.00 ^{d}	0.94 ^{h}	7.66 ^{bc}
T$_2$- BC @ 5 kg plant^{-1} + NPK as per POP	32.50 ^{bcd}	1.36 ^{g}	8.00 ^{bc}
T$_3$- BC @ 10 kg plant^{-1} + NPK as per POP	32.41 ^{bcd}	1.45 ^{ef}	7.00 ^{cd}
T$_4$- BC @ 5 kg plant^{-1} + 75% NPK as per POP	33.16 ^{b}	1.69 ^{c}	9.33 ^{a}
T$_5$- BC @ 10 kg plant^{-1} + 75% NPK as per POP	33.00 ^{bc}	1.56 ^{d}	5.66 ^{e}
T$_6$- FYM 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	32.83 ^{bc}	1.51 ^{de}	7.00 ^{cd}
T$_7$- BC @ 5 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	32.33 ^{cd}	1.42 ^{fg}	6.00 ^{de}
T$_8$- BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	32.98 ^{bc}	1.55 ^{d}	7.66 ^{bc}
T$_9$- BC @ 5 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	32.83 ^{bc}	1.83 ^{b}	8.66 ^{ab}
T$_{10}$- BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	34.00 ^{a}	2.18 ^{a}	9.66 ^{a}
T$_{11}$- BC alone 10 kg plant^{-1}	31.83 ^{d}	0.84 ^{i}	7.66 ^{bc}
SEm (±)	0.15	0.03	0.58
CD (0.05)	0.81	0.08	1.21

*BC-Biochar, FYM-Farm yard manure, STBR-Soil test based recommendation; ^{a,b,c,d,e} Significant difference between treatments

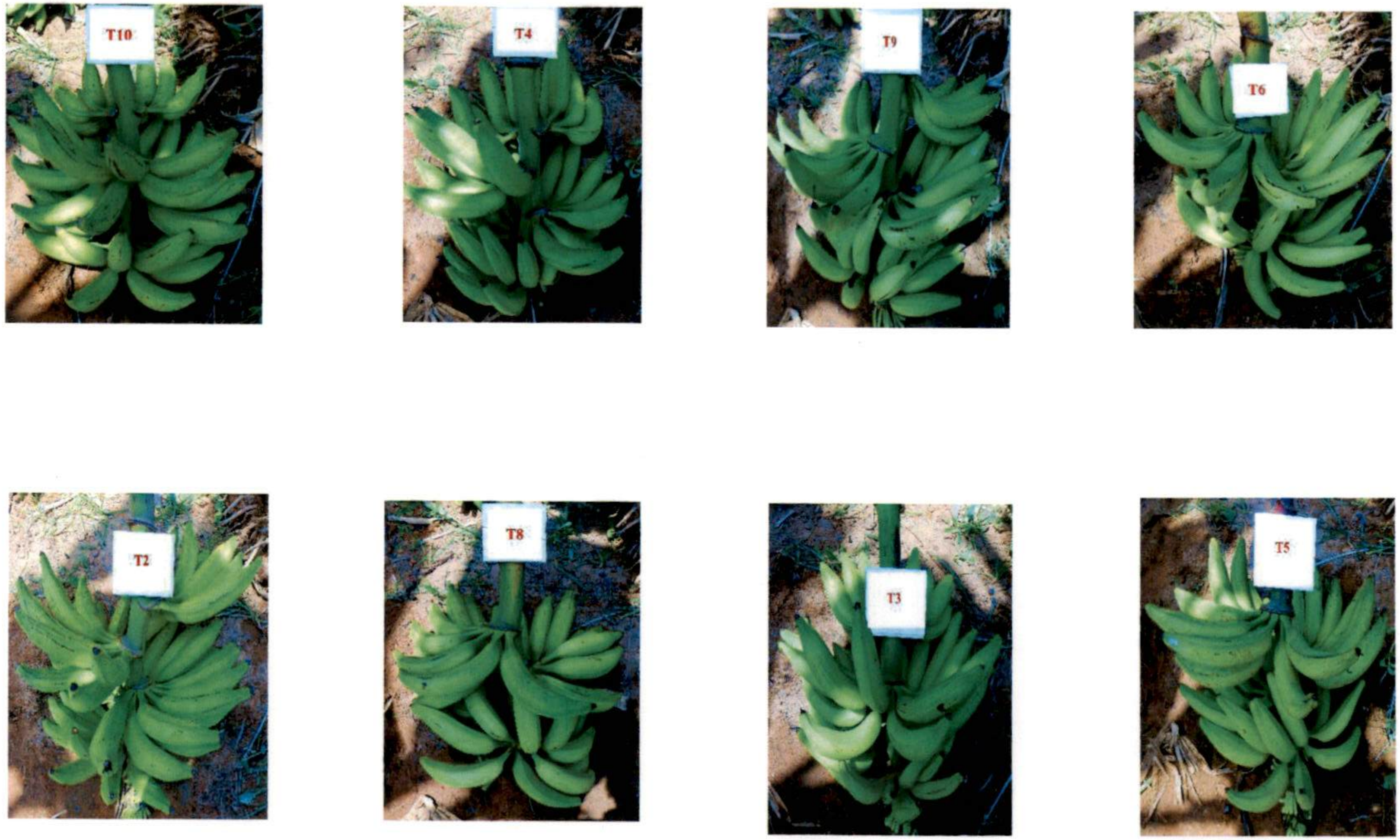


Plate 12. a) Bunch yield of banana in different treatments

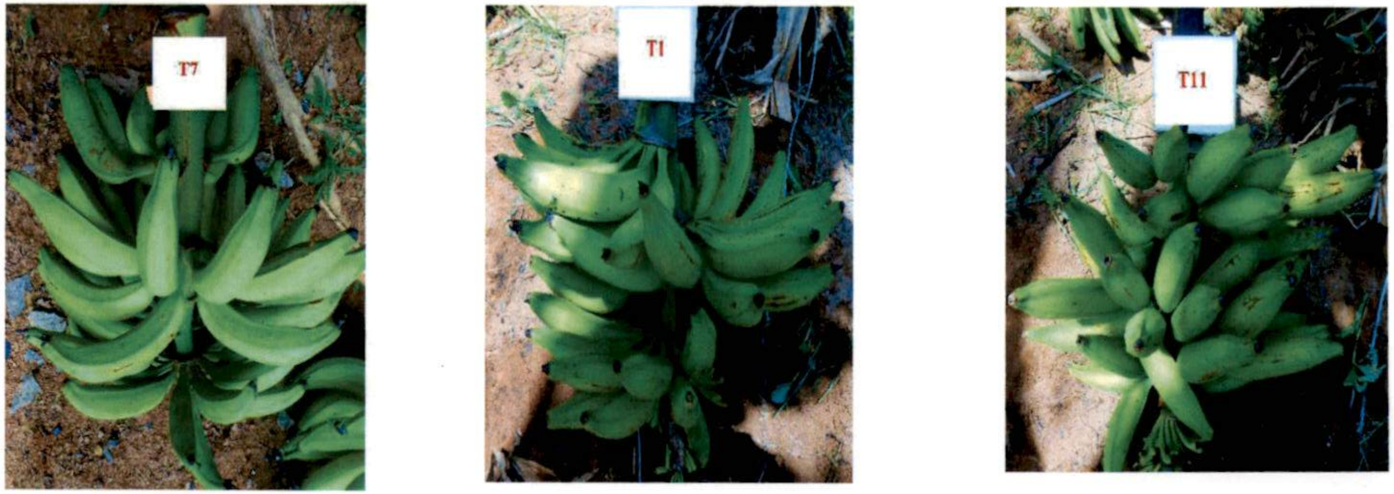


Plate 12. b) Bunch yield of banana in different treatments

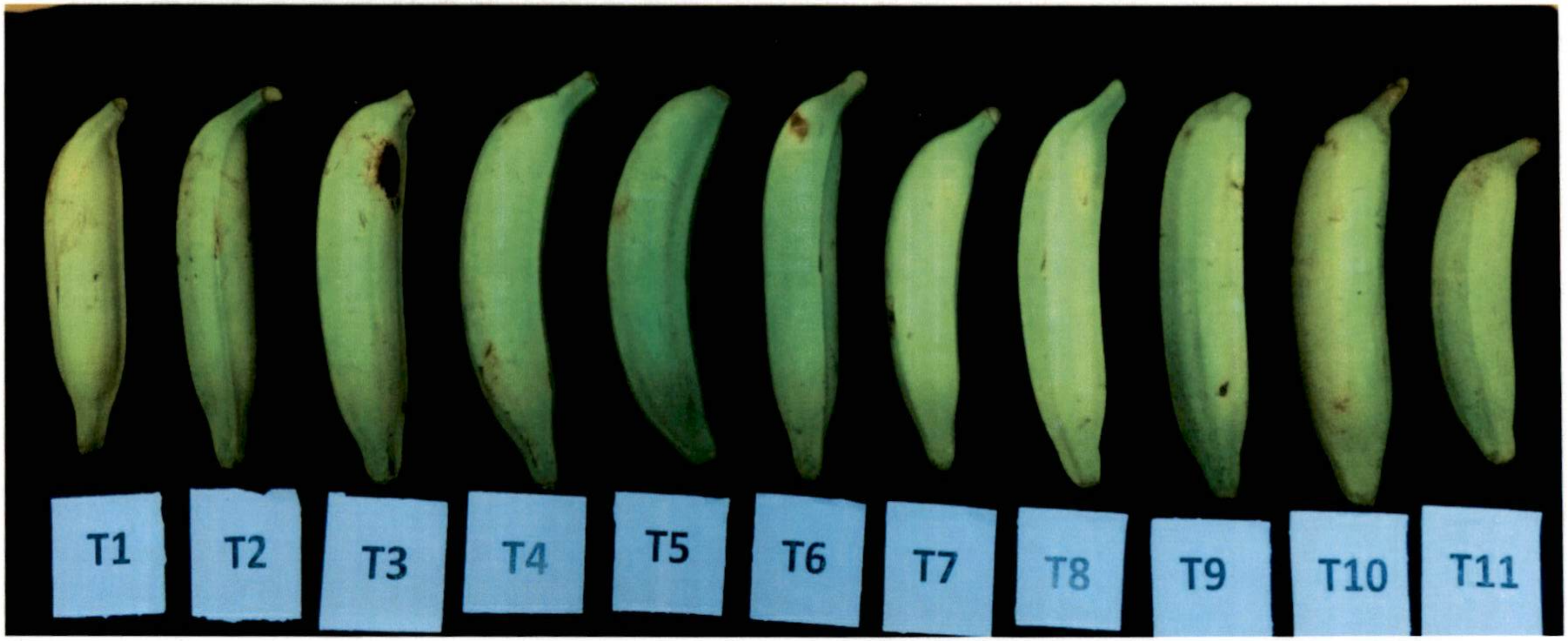
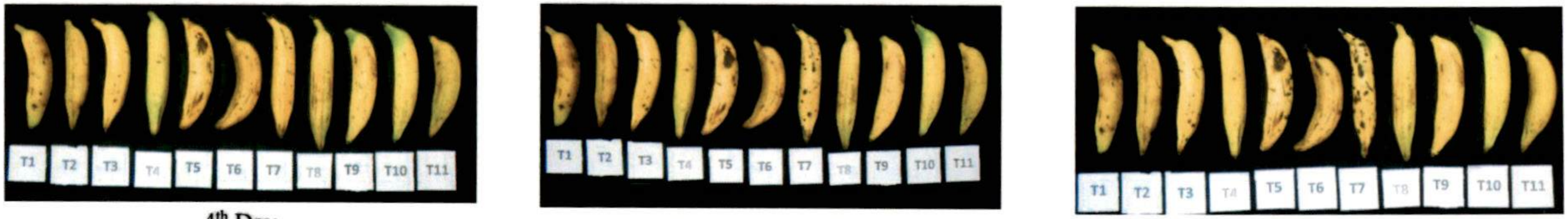


Plate 13. Effect of treatments on index fruit of banana

1st Day

2nd Day

3rd Day



4th Day

5th Day

6th Day

7th Day

8th Day

9th Day

Plate 14. Biochar based different treatments effect on shelf life of banana

4.2.7 Incidence of Pests and Diseases

Table 18 outline the details regarding the incidence of pests and diseases noticed during the crop growth period. Pest infested and disease affected leaves were cut and burnt. A blanket spraying of Ekalux 2 mL L^{-1} was given for controlling *Spodoptera litura* . Sigatoka leaf spot was brought under control with a single foliar spray of Indofil M 45 @ 3 g L^{-1}.

Table 18. Incidence of pests and disease (%) in the field experiment

	Percentage incidence (%)
Pests	
Spodoptera litura	5.27
Disease	
Sigatoka leaf spot	11.84

4.3 EFFECT OF BIOCHAR ON SOIL HEALTH AND CROP PRODUCTIVITY

The results of the field experiment conducted to study the effect of biochar on soil health and crop productivity using banana as test crop are presented in this session.

4.3.1 Effect of Biochar on Soil Fertility Parameters

4.3.1.1 Effect of Treatments on Physical properties of soil

The physical properties of the soil at final harvest stage are presented in Table 19. 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 is observed from the data that the water holding capacity of the soil was significantly influenced by the treatments at the final harvest stage (Table 19). The highest WHC value of 38.18 % was recorded in the treatment BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR (T_{10}). This was on par with BC @ 10 kg plant^{-1} + 75% NPK as per POP (T_5), BC @ 10 kg plant^{-1} + NPK as per POP (T_3), BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR) (T_8), BC @ 5 kg plant^{-1} + NPK as per POP (T_2) and BC alone 10 kg plant^{-1} (T_{11}) which was following the values of 36.6 %, 36.23 %, 35.98 %, 34.80 % and 33.76% respectively. The lowest value of 24.30 % was recorded by the package of practices recommendation (T_1) treatment.

4.3.1.1.2 Bulk Density

As far as the bulk density of the soils in different treatments at final harvest stage are concerned, the effect of treatments are significantly different (Table 19). The highest bulk density at final harvest was 1.32 Mg m^{-3} by package of practices recommendation (T_1) and the lowest (1.23 Mg m^{-3}) for BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T_{10}). Bulk density followed the order package of practices recommendation (T_1) > BC alone 10 kg plant^{-1} (T_{11}) > BC @ 5 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR) (T_7) > BC

88

@ 5 kg plant^{-1} + 75% NPK as per POP (T_4) > BC @ 5 kg plant^{-1} + 75% NPK as per POP (T_2) > BC @ 5 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T_9) > FYM 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR) (T_6) > BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR) (T_8) > BC @ 10 kg plant^{-1} + 75% NPK as per POP (T_5) > BC @ 10 kg plant^{-1} + NPK as per POP (T_3) > BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T_{10}) at final harvest stage.

4.3.1.1.3 Porosity

Analysis of the data indicated that percent soil porosity were significantly influenced by the application of treatments (Table 19). At final harvest stage, porosity was superior for the treatment BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T_{10}) which recorded a value of 58.35 %, which was on par with BC @ 10 kg plant^{-1} + 75% NPK as per POP (T_5), BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR) (T_8), FYM 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR) (T_6) and BC @ 10 kg plant^{-1} + 75% NPK as per POP (T_3) values of 55.41 %, 55.15 %, 53.65 % and 53.06 % respectively. The lowest percent of porosity was shown by package of practices recommendation (T_1) with a value of 43.12 %.

4.3.1.2 Effect of Treatments on Electro-Chemical and Chemical Properties of Soil

The data on electro-chemical and chemical properties of soil by the application of treatments are presented in Table 20.

4.3.1.2.1 pH

A significant effect in the soil pH was evident at the final harvest stage in various treatments as provided in Table 20. At final harvest stage there was an increase in soil pH from the initial value of 4.73 in all treatments. Application of BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T_{10}) was found with the significantly superior value of 5.17, which was on par with BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR) (T_8) (5.11),

89

BC @ 10 kg plant^{-1} + 75% NPK as per POP (T_3) (5.09), FYM 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR) (T_6) (5.05) and BC @ 5 kg plant^{-1} + 75% NPK as per POP (T_4) (4.97) treatments. The lowest value of 4.57 was recorded by T_1 (Package of practices recommendation) at harvest stage.

4.3.1.2.2 Electrical Conductivity (EC)

Final harvest stage determination of EC of the soil samples revealed variation among the different treatments as is given in Table 20. The highest EC value noticed in the entire field experiment was 0.212 dS m^{-1} which was recorded in BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T_{10}) treatment and the lowest (0.088 dS m^{-1}) for package of practices recommendation (T_1). EC followed the order BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T_{10}) > BC @ 5 kg plant^{-1} + 75% NPK as per POP (T_4) > BC alone 10 kg plant^{-1} (T_{11}) > BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR) (T_8) > BC @ 5 kg plant^{-1} + NPK as per POP (T_2), BC @ 10 kg plant^{-1} + 75% NPK as per POP (T_5) > BC @ 5 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR) (T_7) > BC @ 5 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T_9) > FYM 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR) (T_6) > BC @ 10 kg plant^{-1} + NPK as per POP (T_3) > Package of practices recommendation (T_1).

4.3.1.2.3 Cation Exchange Capacity (CEC)

Perusal of the data revealed that there was significant difference between the treatments at final harvest stage with respect to soil CEC (Table 20). The initial soil had CEC of 3.36 cmol kg^{-1}. At final harvest stage BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T_{10}) recorded significantly superior value of 5.18 cmol kg^{-1} which was on par with T_5 (5.07 cmol kg^{-1}), T_3 (4.92 cmol kg^{-1}) and T_4 (4.85 cmol kg^{-1}) treatments. The lowest soil CEC of 2.59 cmol kg^{-1} was found in the package of practices recommendation (T_1) treatment.

Table 19. Effect of treatments on soil physical properties

	Water holding capacity (%)	Bulk density (Mg m^{-3})	Porosity (%)
T$_1$- Package of practices recommendation	24.30^{e}	1.32^{a}	43.12^{d}
T$_2$- BC @ 5 kg plant^{-1} + NPK as per POP	34.80^{abc}	1.27^{bcd}	49.56^{bc}
T$_3$- BC @ 10 kg plant^{-1} + NPK as per POP	36.23^{ab}	1.24^{de}	53.06^{ab}
T$_4$- BC @ 5 kg plant^{-1} + 75% NPK as per POP	32.25^{bcd}	1.27^{bcd}	51.14^{bc}
T$_5$- BC @ 10 kg plant^{-1} + 75% NPK as per POP	36.60^{ab}	1.24^{cde}	55.41^{ab}
T$_6$- FYM 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	26.15^{e}	1.25^{cde}	53.65^{ab}
T$_7$- BC @ 5 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	28.47^{de}	1.27^{bc}	49.71^{bc}
T$_8$- BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	35.98^{ab}	1.24^{cde}	55.15^{ab}
T$_9$- BC @ 5 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	29.58^{cde}	1.26^{cde}	51.25^{bc}
T$_{10}$- BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	38.18^{a}	1.23^{e}	58.35^{a}
T$_{11}$- BC alone 10 kg plant^{-1}	33.76^{abcd}	1.29^{ab}	45.83^{cd}
SEm (±)	2.54	0.01	2.94
CD (0.05)	5.31	0.03	6.14

*BC-Biochar, FYM-Farm yard manure, STBR-Soil test based recommendation; ^{a,b,c,d,e} Significant difference between treatments

Table 20. Effect of treatments on soil electro-chemical and chemical properties

	pH	EC (dS m^{-1})	CEC (cmol kg^{-1})	OC (%)
T$_1$- Package of practices recommendation	4.57^{d}	0.088^{i}	2.59^{f}	1.12^{f}
T$_2$- BC @ 5 kg plant^{-1} + NPK as per POP	4.86^{be}	0.128^{de}	3.89^{de}	1.29^{cd}
T$_3$- BC @ 10 kg plant^{-1} + NPK as per POP	5.09^{a}	0.100^{h}	4.92^{abc}	1.43^{ab}
T$_4$- BC @ 5 kg plant^{-1} + 75% NPK as per POP	4.97^{abc}	0.177^{b}	4.85^{abc}	1.34^{ab}
T$_5$- BC @ 10 kg plant^{-1} + 75% NPK as per POP	5.05^{ab}	0.115^{ef}	5.07^{ab}	1.40^{ab}
T$_6$- FYM 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	4.75^{cd}	0.102^{gh}	3.42^{e}	1.18^{ef}
T$_7$- BC @ 5 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	4.83^{bc}	0.116^{fg}	4.52^{bc}	1.23^{de}
T$_8$- BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	5.11^{a}	0.129^{d}	5.10^{ab}	1.44^{a}
T$_9$- BC @ 5 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	4.83^{bc}	0.117^{fgh}	4.90^{abc}	1.34^{bc}
T$_{10}$- BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	5.17^{a}	0.212^{a}	5.18^{a}	1.45^{a}
T$_{11}$- BC alone 10 kg plant^{-1}	4.86^{cd}	0.136^{c}	4.41^{cd}	1.29^{cd}
SEm (±)	010	0.004	0.28	0.04
CD (0.05)	2.57	0.009	0.59	0.09

*BC-Biochar, FYM-Farm yard manure, STBR-Soil test based recommendation; ^{a,b,c,d,e} Significant difference between treatments

4.3.1.2.4 Organic Carbon

The initial organic carbon content of soil was 1.13 % and an increase was observed in the values by the application of biochar treatments at final harvest stage (Table 20). Significantly superior value of 1.45 % was observed in BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T_{10}), which was on par with T_8 (BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR)) (1.44 %), T_3 (BC @ 5 kg plant^{-1} + NPK as per POP) (1.43 %) and T_5 (BC @ 10 kg plant^{-1} + 75% NPK as per POP) (1.4 %). This was followed by T_4 (BC @ 5 kg plant^{-1} + 75% NPK as per POP) (1.34 %) and T_9 (BC @ 5 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR)) (1.34 %), which were superior to the remaining treatments. The package of practices recommendation (T_1) treatment recorded the lowest organic carbon of 1.12 % at final harvest stage.

4.3.1.2.5 Available Nitrogen

Soil analysis at different growth stages revealed significant variation in the available N content which is given in the Table 21. It is evident from the data that by the application of treatments, there was increase in the availability of N in soil at 6 MAP, followed by a decrease due to uptake of N by the plant at final harvest stage. At 3 MAP, application of BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR) (T_8) recorded highest availability of N content in soil (272.24 kg ha^{-1}), which was significantly higher than all other treatments except BC @ 10 kg plant^{-1} + 75 % (NPK + secondary & micronutrients as per STBR) (T_{10}) (269.12 kg ha^{-1}) and FYM 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR) (T_6) (266.38 kg ha^{-1}), which were found to be on par. The lowest value of 210.09 kg ha^{-1} was recorded by the T_{11} treatment that received BC alone 10 kg plant^{-1}. At 6 MAP, application of BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T_{10}) registered significantly higher value of 296.38 kg ha^{-1}, followed by BC 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR) (T_8), BC @ 10 kg plant^{-1} + 75 % as per POP (T_5) which was on par with BC @ 5 kg plant^{-1} + 75 % NPK as per POP (T_4) and FYM 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR) (T_6) and BC 5 kg plant^{-1} + (NPK +

secondary & micronutrients as per STBR) (T_7) registering values of 285.21kg ha^{-1}, 285.20 kg ha^{-1}, 285.20 kg ha^{-1} and 283.05 kg ha^{-1} respectively. BC alone 10 kg plant^{-1} (T_{11}) recorded the lowest content of N availability at 6 MAP (222.45 kg ha^{-1}). At the final harvest stage also, there was significant difference between the treatments. A decrease in the value of available N content in soil was observed than that at 6 MAP invariably in all treatments. T_{10} which received BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) recorded the highest value of 280.09 kg ha^{-1} which was on par with all other treatments except BC @ 5 kg plant^{-1} + 75% NPK as per POP (T_4), BC @ 5 kg plant^{-1} + NPK as per POP (T_2), package of practices recommendation (T_1) and BC alone 10 kg plant^{-1} (T_{11}).

4.3.1.2.6 Available Phosphorus

An increasing trend in available P status was noticed by the application of treatments when compared to the initial value of 80.40 kg ha^{-1} at 3 MAP and 6 MAP stages which later decreased at final harvest stage due to P uptake by the plant (Table 22). However, at 3 MAP stage BC @ 5 kg plant^{-1} + NPK as per POP (T_2) recorded the highest value of 117.37 kg ha^{-1} which was on par with all other treatments except BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR) (T_8) and BC alone 10 kg plant^{-1} (T_{11}) which registered lowest values of 95.09 kg ha^{-1} and 57.14 kg ha^{-1} respectively. At 6 MAP stage, there was significant difference between the treatments. Application of BC @ 10 kg plant^{-1} + NPK as per POP (T_3) recorded the highest value of 138.17 kg ha^{-1} which was on par with BC @ 5 kg plant^{-1} + 75% NPK as per POP (T_4) (134.91 kg ha^{-1}), BC @ 5 kg plant^{-1} + NPK as per POP BC @ 5 kg plant^{-1} + NPK as per POP (T_2) (134.82 kg ha^{-1}), BC @ 10 kg plant^{-1} + 75% NPK as per POP (T_5) (129.87 kg ha^{-1}) and Package of practices recommendation (T_1) (125.48 kg ha^{-1}). The lowest value of 35.66 kg ha^{-1} was recorded by BC alone 10 kg plant^{-1} (T_{11}). A decrease in the value of available P in soil at final harvest stage was observed than that at 6 MAP stage and there was significant difference between the treatments. Application of BC @ 10 kg plant^{-1} + NPK as per POP (T_3) recorded the superior value of 117.65 kg ha^{-1} which was found to be on par with BC @ 10 kg plant^{-1} + NPK as per POP (T_3) and BC @ 10 kg plant^{-1} + 75% NPK as per POP (T_5). The lowest value of 34.52 kg ha^{-1} was recorded by the T_{11} treatment (BC alone 10 kg plant^{-1}).

4.3.1.2.7 Available Potassium

It is evident from the data that with the application of biochar, there was an increase in the availability of K in soil at 6 MAP stage, followed by a decrease due to uptake of K by the plant at final harvest stage (Table 23). There was no significant difference between the treatments in K availability at 3 MAP. At 6 MAP stage highest availability of K was recorded by BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T_{10}) with a value of 238.13 kg ha^{-1}, which was significantly higher than all other treatments except T_8 (234.80 kg ha^{-1}), T_6 (232.80 kg ha^{-1}) and T_7 (226 kg ha^{-1}) treatments which were found to be on par. At the final harvest stage also, the same trend was observed. The significantly highest value of 228.40 kg ha^{-1} was recorded by BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T_{10}) which was on par with T_8 (222.13 kg ha^{-1}), T_9 (218.40 kg ha^{-1}), T_4 (217.60 kg ha^{-1}) and T_6 (216.66 kg ha^{-1}) compared to all other treatments. The lowest value of 159.60 kg ha^{-1} was recorded by BC @ 5 kg plant^{-1} + NPK as per POP (T_1).

4.3.1.2.8 Available Calcium

A similarity was observed in the Ca release pattern (Table 24) of almost all the treatments at all the three crop growth stages. It is evident from the data that by the application of treatments, there was an increase in the availability of Ca in soil at 6 MAP, followed by a decrease due to uptake of Ca by the plant at final harvest stage. It was observed that BC @ 10 kg plant^{-1} + NPK as per POP (T_3) treatment attained significantly highest available Ca at the 3 MAP, 6 MAP and at final harvest stages with values of 447.50 mg kg^{-1}, 451.45 mg kg^{-1} and 434. 66 mg kg^{-1} respectively. The treatment BC alone 10 kg plant^{-1} (T_{11}) recorded the lowest available Ca in soil at different stages.

Table 21. Effect of treatments on soil available N at different growth stages, kg ha^{-1}

	3 MAP	6 MAP	HS
T_1- Package of practices recommendation	230.30^{d}	264.82^{e}	244.60^{c}
T_2- BC @ 5 kg plant^{-1} + NPK as per POP	233.64^{d}	263.42^{e}	250.09^{bc}
T_3- BC @ 10 kg plant^{-1} + NPK as per POP	246.38^{c}	276.38^{cd}	256.38^{abc}
T_4- BC @ 5 kg plant^{-1} + 75% NPK as per POP	246.97^{c}	266.75^{e}	255.20^{bc}
T_5- BC @ 10 kg plant^{-1} + 75% NPK as per POP	257.56^{b}	285.20^{b}	265.79^{abc}
T_6- FYM 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	266.38^{a}	285.20^{b}	264.60^{abc}
T_7- BC @ 5 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	256.97^{b}	283.05^{bc}	260.68^{abc}
T_8- BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	272.24^{a}	285.20^{b}	270.57^{ab}
T_9- BC @ 5 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	255.20^{b}	270.09^{de}	265.20^{abc}
T_{10}- BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	269.12^{a}	296.38^{a}	280.09^{a}
T_{11}- BC alone 10 kg plant^{-1}	210.09^{e}	222.45^{f}	188.16^{d}
SEm (±)	3.60	4.05	11.58
CD (0.05)	7.53	8.46	24.16

*BC-Biochar, FYM-Farm yard manure, STBR-Soil test based recommendation; ^{a,b,c,d,e} Significant difference between treatments

Table 22. Effect of treatments on soil available P at different growth stages, kg ha^{-1}

	3 MAP	6 MAP	HS
T_1- Package of practices recommendation	106.86^{ab}	125.48^{ab}	101.02^{bc}
T_2- BC @ 5 kg plant^{-1} + NPK as per POP	117.37^{a}	134.82^{a}	114.95^{a}
T_3- BC @ 10 kg plant^{-1} + NPK as per POP	113.07^{ab}	138.17^{a}	117.65^{a}
T_4- BC @ 5 kg plant^{-1} + 75% NPK as per POP	104.79^{ab}	134.91^{a}	99.40^{bc}
T_5- BC @ 10 kg plant^{-1} + 75% NPK as per POP	112.09^{ab}	129.87^{a}	105.88^{ab}
T_6- FYM 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	98.14^{ab}	99.44^{c}	82.73^{d}
T_7- BC @ 5 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	99.41^{ab}	102.03^{bc}	90.78^{cd}
T_8- BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	95.09^{b}	105.27^{bc}	93.28^{bcd}
T_9- BC @ 5 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	97.70^{ab}	102.24^{bc}	93.76^{bcd}
T_{10}- BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	100.84^{ab}	105.33^{bc}	99.12^{bc}
T_{11}- BC alone 10 kg plant^{-1}	57.14^{c}	35.66^{d}	34.52^{e}
SEm (±)	10.14	11.74	6.63
CD (0.05)	21.17	24.50	13.84

*BC-Biochar, FYM-Farm yard manure, STBR-Soil test based recommendation; ^{a,b,c,d,e} Significant difference between treatments

Table 23. Effect of treatments on soil available K at different growth stages, kg ha^{-1}

	3 MAP	6 MAP	HS
T$_1$- Package of practices recommendation	147.33	186.40 ^{d}	159.60 ^{d}
T$_2$- BC @ 5 kg plant^{-1} + NPK as per POP	160.13	218.00 ^{c}	183.86 ^{c}
T$_3$- BC @ 10 kg plant^{-1} + NPK as per POP	163.60	217.73 ^{c}	194.66 ^{c}
T$_4$- BC @ 5 kg plant^{-1} + 75% NPK as per POP	169.33	223.73 ^{bc}	216.93 ^{ab}
T$_5$- BC @ 10 kg plant^{-1} + 75% NPK as per POP	160.80	218.00 ^{c}	217.60 ^{ab}
T$_6$- FYM 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	174.26	232.80 ^{ab}	216.66 ^{ab}
T$_7$- BC @ 5 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	157.20	226.00 ^{abc}	210.06 ^{b}
T$_8$- BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	171.46	234.80 ^{ab}	222.13 ^{ab}
T$_9$- BC @ 5 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	163.20	222.66 ^{bc}	218.40 ^{ab}
T$_{10}$- BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	181.60	238.13 ^{a}	228.40 ^{a}
T$_{11}$- BC alone 10 kg plant^{-1}	142.80	167.33 ^{e}	162.40 ^{d}
SEm (±)	19.01	6.15	6.02
CD (0.05)	NS	12.83	12.56

*BC-Biochar, FYM-Farm yard manure, STBR-Soil test based recommendation; ^{a,b,c,d,e} Significant difference between treatments

Table 24. Effect of treatments on soil available Ca at different growth stages, mg kg^{-1}

	3 MAP	6 MAP	HS
T$_1$- Package of practices recommendation	388.12 ^{c}	391.12 ^{c}	371.64 ^{d}
T$_2$- BC @ 5 kg plant^{-1} + NPK as per POP	424.16 ^{b}	425.83 ^{b}	401.43 ^{bc}
T$_3$- BC @ 10 kg plant^{-1} + NPK as per POP	447.50 ^{a}	451.45 ^{a}	434.66 ^{a}
T$_4$- BC @ 5 kg plant^{-1} + 75% NPK as per POP	410.20 ^{b}	418.54 ^{b}	390.43 ^{c}
T$_5$- BC @ 10 kg plant^{-1} + 75% NPK as per POP	422.70 ^{b}	426.14 ^{b}	409.45 ^{b}
T$_6$- FYM 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	366.87 ^{d}	384.00 ^{c}	342.58 ^{e}
T$_7$- BC @ 5 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	359.79 ^{d}	356.81 ^{d}	328.66 ^{ef}
T$_8$- BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	360.95 ^{d}	358.77 ^{d}	336.06 ^{ef}
T$_9$- BC @ 5 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	358.54 ^{d}	354.96 ^{d}	328.02 ^{ef}
T$_{10}$- BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	356.25 ^{de}	357.77 ^{d}	338.45 ^{ef}
T$_{11}$- BC alone 10 kg plant^{-1}	340.62 ^{e}	335.41 ^{e}	320.31^{f}
SEm (±)	7.79	7.46	8.97
CD (0.05)	16.26	15.58	18.73

*BC-Biochar, FYM-Farm yard manure, STBR-Soil test based recommendation; ^{a,b,c,d,e} Significant difference between treatments

4.3.1.2.8 Available Magnesium

An increase in the availability of Mg in soil at 6 MAP stage, followed by a decrease due to uptake of Mg by the plant at final harvest stage was observed in all treatments (Table 25). It has been statistically observed that application of treatments had significance on available Mg in soil at 6 MAP and final harvest stages. There was no significant difference between the treatments in availability of Mg at 3 MAP stage. At 6 MAP stage BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T_{10}) recorded the highest value of 88.75 mg kg^{-1} and this data was found to be on par with T_8 (81.68 mg kg^{-1}), T_9 (76.81 mg kg^{-1}) and T_7 (76.18 mg kg^{-1}) compared to all other treatments. At final harvest stage also, the same trend continued and there was slight decrease in available Mg content in soil. At final harvest stage application of BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T_{10}) recorded superior value of 72.56 mg kg^{-1} compared to all other treatments except T_8 (69.20 mg kg^{-1}), T_9 (68.47 mg kg^{-1}), T_6 (66.12 mg kg^{-1}) and T_5 (64.45 mg kg^{-1}) were found to be on par. BC alone 10 kg plant^{-1} (T_{11}) treatment recorded the lowest available of Mg in soil, value of 45.47 mg kg^{-1}.

4.3.1.2.9 Available Sulphur

The analysis data revealed that treatments had significant influence on available S status in soil at different stages (Table 26). It is evident from the data that by the application of treatments, there was increase in the availability of S in soil at 6 MAP, followed by a decrease due to uptake of S by the plant at final harvest stage. Application of BC @ 10 kg plant^{-1} + 75 % (NPK + secondary & micronutrients as per STBR) (T_{10}) recorded highest available S in soil with a value of 33 mg kg^{-1} which was on par with T_8 (31.86 mg kg^{-1}), T_6 (28.47 mg kg^{-1}) and T_7 (28.42 mg kg^{-1}) compared to all other treatments. At 6 MAP stage, BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR) (T_8) recorded highest available S (36.18 mg kg^{-1}) in soil compared to all other treatments except T_9 (36.01 mg kg^{-1}), T_{10} (35.21 mg kg^{-1}), T_6 (34.63 mg kg^{-1}) and T_7 (30.63 mg kg^{-1}) treatments which were found to be on par. Application of BC @ 10 kg plant^{-1} + 75% (NPK +

secondary and micronutrients as per STBR) (T_{10}) recorded the superior value of 34.46 mg kg^{-1} which was found to be on par with T_9 (34.12 mg kg^{-1}), T_6 (32.09 mg kg^{-1}) and T_8 (31.58 mg kg^{-1}). The lowest value of 16.25 mg kg^{-1} was recorded by the treatments that received BC alone @ 10 kg plant^{-1} (T_{11}).

4.3.1.2.10 Available Zinc

Perusal of the data revealed that application of biochar had significant influence on available Zn in soil at different stages of crop growth (Table 27). It is evident from the data that by the application of treatments, there was increase in the availability of Zn in soil at 6 MAP, followed by a decrease due to uptake of Zn by the plant at final harvest stage. At 3 MAP stage, it was observed that BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T_{10}) treatment was found significantly highest available Zn in soil with a value of 3.13 mg kg^{-1}, which was on par with T_4 (2.91 mg kg^{-1}), T_6 (2.89 mg kg^{-1}) and T_8 (2.87 mg kg^{-1}) as compared to all other treatments. At 6 MAP stage, significantly highest value of 3.34 mg kg^{-1} was recorded by BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T_{10}) which was on par with T_4 (3.19 mg kg^{-1}), T_8 (2.96 mg kg^{-1}) and T_9 (2.93 mg kg^{-1}) compared to all other treatments. The lowest value of 2.07 mg kg^{-1} was recorded by BC @ 5 kg plant^{-1} + NPK as per POP (T_1). At final harvest stage also, the same trend was observed. The significantly highest availability of Zn was recorded by BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T_{10}) with a value of 2.55 mg kg^{-1}, which was on par with all other treatments except T_3 (2.13 mg kg^{-1}), T_6 (2.07 mg kg^{-1}), T_{11} (1.69 mg kg^{-1}) and T_1 (1.36 mg kg^{-1}) treatments.

4.3.1.2.11 Available Copper

There was increase in the availability of Cu in soil at 6 MAP stage, followed by a decrease due to uptake of Cu by the plant at final harvest stage in all the treatments. It was clear from the data that treatments had significant influence on the content of available Cu in soil at 3 MAP and final harvest stages (Table 28). Application of BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T_{10}) recorded the highest values of 3.20 mg kg^{-1} and 2.79 mg kg^{-1} at 3 MAP and final harvest stages. There was no significant difference between the treatments in availability of Cu at 6 MAP. Application of BC alone 10 kg $plant^{-1}$ (T_{11}) recorded the lowest available Cu in soil at different crop growth stages.

4.3.1.2.12 Available Boron

It was statistically observed that application of treatments had significance on available B in soil at 6 MAP and final harvest stages. There was an increase in the availability of B in soil at 6 MAP stage, followed by a decrease due to uptake of B by the plant at final harvest stage (Table 29). There was no significant difference between the treatments in availability of B at 3 MAP. Application of BC @ 10 kg $plant^{-1}$ + 75% (NPK + secondary & micronutrients as per STBR) (T_{10}) recorded the highest values of 1.25 mg kg^{-1} and 0.92 mg kg^{-1}, at 6 MAP and final harvest stages respectively. The lowest values of 0.55 mg kg^{-1} and 0.51 mg kg^{-1} were recorded by the package of practices recommendation (T_1) treatment at 6 MAP and final harvest stages.

4.3.1.3 Effect of Treatments on Biological Properties of Soil

4.3.1.3.1 *Dehydrogenase Activity*

The effect of biochar based treatments on the dehydrogenase activity in the soil at final harvest stage is given in Table 30. The highest significant dehydrogenase activity in soil was obtained in BC @ 10 kg $plant^{-1}$ + 75% (NPK + secondary & micronutrients as per STBR) (T_{10}) (64.87 µg TPF g^{-1}) which was on par with BC @ 10 kg $plant^{-1}$ + NPK as per POP (T_3) (59.18 µg TPF g^{-1}) and BC @ 10 kg $plant^{-1}$ + (NPK + secondary & micronutrients as per STBR) (T_8) (58.19 µg TPF g^{-1}). Package of practices recommendation (T_1) recorded lowest value of 41.61 µg TPF g^{-1}.

Table 25. Effect of treatments on soil available Mg at different growth stages, mg kg^{-1}

	3 MAP	6 MAP	HS
T$_1$- Package of practices recommendation	62.70	56.75 ^{cd}	46.08 ^{d}
T$_2$- BC @ 5 kg plant^{-1} + NPK as per POP	66.79	71.47 ^{b}	50.00 ^{cd}
T$_3$- BC @ 10 kg plant^{-1} + NPK as per POP	68.52	69.60 ^{bc}	51.33 ^{cd}
T$_4$- BC @ 5 kg plant^{-1} + 75% NPK as per POP	69.33	72.52 ^{b}	60.08 ^{bc}
T$_5$- BC @ 10 kg plant^{-1} + 75% NPK as per POP	72.00	74.77 ^{b}	64.45 ^{ab}
T$_6$- FYM 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	65.12	73.35 ^{b}	66.12 ^{ab}
T$_7$- BC @ 5 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	72.45	76.18 ^{ab}	61.75 ^{b}
T$_8$- BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	73.18	81.68 ^{ab}	69.20 ^{ab}
T$_9$- BC @ 5 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	74.37	76.81 ^{ab}	68.47 ^{ab}
T$_{10}$- BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	79.83	88.75 ^{a}	72.56 ^{a}
T$_{11}$- BC alone 10 kg plant^{-1}	50.93	51.95 ^{d}	45.47 ^{d}
SEm (±)	5.32	6.52	4.94
CD (0.05)	NS	13.62	10.31

*BC-Biochar, FYM-Farm yard manure, STBR-Soil test based recommendation; ^{a,b,c,d,e} Significant difference between treatments

Table 26. Effect of treatments on soil available S at different growth stages, mg kg^{-1}

	3 MAP	6 MAP	HS
T$_1$- Package of practices recommendation	19.77 ^{de}	23.08 ^{fg}	22.42 ^{de}
T$_2$- BC @ 5 kg plant^{-1} + NPK as per POP	23.85 ^{cde}	28.02 ^{cdef}	27.49 ^{bc}
T$_3$- BC @ 10 kg plant^{-1} + NPK as per POP	22.87 ^{cde}	25.38 ^{ef}	21.42 ^{e}
T$_4$- BC @ 5 kg plant^{-1} + 75% NPK as per POP	25.80 ^{c}	28.71 ^{bcdef}	27.58 ^{bc}
T$_5$- BC @ 10 kg plant^{-1} + 75% NPK as per POP	25.44 ^{cd}	27.35 ^{def}	26.41 ^{cd}
T$_6$- FYM 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	28.47 ^{abc}	34.63 ^{abcd}	32.09 ^{ab}
T$_7$- BC @ 5 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	28.42 ^{abc}	30.50 ^{abcde}	28.76 ^{bc}
T$_8$- BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	31.86 ^{ab}	36.18 ^{a}	31.58 ^{ab}
T$_9$- BC @ 5 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	27.08 ^{bc}	36.01 ^{ab}	34.12 ^{a}
T$_{10}$- BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	33.00 ^{a}	35.21 ^{abc}	34.46 ^{a}
T$_{11}$- BC alone 10 kg plant^{-1}	18.36 ^{e}	16.59 ^{g}	16.25 ^{f}
SEm (±)	2.73	3.51	2.27
CD (0.05)	5.71	7.34	4.75

*BC-Biochar, FYM-Farm yard manure, STBR-Soil test based recommendation; ^{a,b,c,d,e} Significant difference between treatments

Table 27. Effect of treatments on soil available Zn at different growth stages, mg kg^{-1}

	3 MAP	6 MAP	HS
T_1- Package of practices recommendation	2.26^{ef}	2.07^{e}	1.36^{d}
T_2- BC @ 5 kg plant^{-1} + NPK as per POP	2.41^{def}	2.62^{bcd}	2.17^{ab}
T_3- BC @ 10 kg plant^{-1} + NPK as per POP	2.63^{bcd}	2.69^{bc}	2.13^{b}
T_4- BC @ 5 kg plant^{-1} + 75% NPK as per POP	2.91^{ab}	3.19^{a}	2.47^{ab}
T_5- BC @ 10 kg plant^{-1} + 75% NPK as per POP	2.39^{def}	2.50^{bcde}	2.35^{ab}
T_6- FYM 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	2.89^{ab}	2.47^{cde}	2.07^{bc}
T_7- BC @ 5 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	2.55^{cde}	2.62^{bcd}	2.43^{ab}
T_8- BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	2.87^{ab}	2.96^{ab}	2.45^{ab}
T_9- BC @ 5 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	2.77^{bc}	2.93^{abc}	2.31^{ab}
T_{10}- BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	3.13^{a}	3.34^{a}	2.55^{a}
T_{11}- BC alone 10 kg plant^{-1}	2.15^{f}	2.22^{de}	1.69^{cd}
SEm (±)	0.13	0.22	0.19
CD (0.05)	0.29	0.46	0.40

*BC-Biochar, FYM-Farm yard manure, STBR-Soil test based recommendation; ^{a,b,c,d,e} Significant difference between treatments

Table 28. Effect of treatments on soil available Cu at different growth stages, mg kg^{-1}

	3 MAP	6 MAP	HS
T_1- Package of practices recommendation	2.38^{e}	2.20	2.55^{bcd}
T_2- BC @ 5 kg plant^{-1} + NPK as per POP	2.90^{b}	2.47	2.67^{abc}
T_3- BC @ 10 kg plant^{-1} + NPK as per POP	2.53^{de}	2.38	2.71^{ab}
T_4- BC @ 5 kg plant^{-1} + 75% NPK as per POP	2.69^{bcd}	2.57	2.50^{bcd}
T_5- BC @ 10 kg plant^{-1} + 75% NPK as per POP	2.48^{de}	2.41	2.48^{cd}
T_6- FYM 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	2.60^{cde}	2.43	2.78^{a}
T_7- BC @ 5 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	2.51^{de}	2.51	2.65^{abc}
T_8- BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	2.82^{bc}	2.56	2.65^{abc}
T_9- BC @ 5 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	3.20^{a}	2.68	2.52^{bcd}
T_{10}- BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	2.86^{bc}	2.56	2.79^{a}
T_{11}- BC alone 10 kg plant^{-1}	2.43^{de}	2.35	2.40^{d}
SEm (±)	0.11	0.23	0.10
CD (0.05)	0.28	NS	0.22

*BC-Biochar, FYM-Farm yard manure, STBR-Soil test based recommendation; ^{a,b,c,d,e} Significant difference between treatments

Table 29. Effect of treatments on soil available B at different growth stages, mg kg^{-1}

	3 MAP	6 MAP	HS
T_1- Package of practices recommendation	0.61	0.55^{e}	0.51^{f}
T_2- BC @ 5 kg plant^{-1} + NPK as per POP	0.71	0.74^{cde}	0.69^{de}
T_3- BC @ 10 kg plant^{-1} + NPK as per POP	0.79	0.83^{cd}	0.73^{bcde}
T_4- BC @ 5 kg plant^{-1} + 75% NPK as per POP	0.88	0.93^{bc}	0.75^{bcd}
T_5- BC @ 10 kg plant^{-1} + 75% NPK as per POP	0.68	0.90^{bcd}	0.71^{cde}
T_6- FYM 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	0.80	0.91^{bcd}	0.74^{bcd}
T_7- BC @ 5 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	0.91	0.93^{bc}	0.79^{bc}
T_8- BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	0.95	1.09^{ab}	0.81^{b}
T_9- BC @ 5 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	0.87	0.95^{bc}	0.71^{cde}
T_{10}- BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	1.13	1.25^{a}	0.92^{a}
T_{11}- BC alone 10 kg plant^{-1}	0.60	0.71^{de}	0.64^{e}
SEm (±)	0.11	0.10	0.04
CD (0.05)	NS	0.21	0.09

*BC-Biochar, FYM-Farm yard manure, STBR-Soil test based recommendation; ^{a,b,c,d,e} Significant difference between treatments

Table 30. Effect of treatments on soil dehydrogenase activity, µg TPF g^{-1} soil 24 h^{-1}

	dehydrogenase activity (µg TPF g^{-1})
T_1- Package of practices recommendation	41.61^{d}
T_2- BC @ 5 kg plant^{-1} + NPK as per POP	50.49^{bcd}
T_3- BC @ 10 kg plant^{-1} + NPK as per POP	59.18^{ab}
T_4- BC @ 5 kg plant^{-1} + 75% NPK as per POP	52.02^{bc}
T_5- BC @ 10 kg plant^{-1} + 75% NPK as per POP	58.01^{ef}
T_6- FYM 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	49.35^{cd}
T_7- BC @ 5 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	53.14^{bc}
T_8- BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	58.19^{abc}
T_9- BC @ 5 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	54.66^{bc}
T_{10}- BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	64.87^{a}
T_{11}- BC alone 10 kg plant^{-1}	52.37^{bc}
SEm (±)	4.62
CD (0.05)	9.64

*BC-Biochar, FYM-Farm yard manure, STBR-Soil test based recommendation; ^{a,b,c,d,e} Significant difference between treatments

4.3.2 Foliar Nutrient Concentration of Nendran Banana as Influenced by Biochar Application

The data on the effect of different treatments on foliar nutrient concentrations namely major, secondary and micronutrients are presented in Tables 31 to 34.

4.3.2.1 Foliar Nitrogen

The index leaf tissue analysis revealed significant difference in the foliar N concentration among the treatments at harvest stage of Nendran banana (Table 31). Highest Foliar N concentration was recorded with the application of BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T$_{10}$) with 6.40 % which was on par with BC @ 5 kg plant^{-1} + 75% NPK as per POP (T$_4$) (6.39 %), BC 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR) (T$_8$) (6.36 %) and BC @ 5 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T$_9$) (6.18 %) and significantly higher than all other treatments. The lowest foliar N concentration was in the range of 4.60 % recorded by BC alone 10 kg plant^{-1} (T$_{11}$) at harvest stage.

4.3.2.2 Foliar Phosphorus

Highest concentration of foliar P ranged from 0.31% in BC @ 5 kg plant^{-1} + 75% NPK as per POP (T$_4$) to 0.17 % in Package of practices recommendation (T$_1$) at final harvest stage (Table 31). The P concentration level followed the order BC @ 5 kg plant^{-1} + 75% NPK as per POP (T$_4$) > BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T$_{10}$) > FYM 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR) (T$_6$) > BC @ 5 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T$_9$) > BC @ 5 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR) (T$_7$) > BC @ 5 kg plant^{-1} + NPK as per POP (T$_2$) > BC @ 10 kg plant^{-1} + NPK as per POP (T$_3$) > BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR) (T$_8$) > BC @ 10 kg plant^{-1} + 75% NPK as per POP (T$_5$) > Package of practices recommendation (T$_1$) > BC alone 10 kg plant^{-1} (T$_{11}$) at the harvest stage.

4.3.2.3 Foliar Potassium

The foliar K concentration of different treatments exhibited significant variation at harvest stage of Nendran banana (Table 31). Highest K concentration was recorded with the application of BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T_{10}) with 2.24 % which was on par with BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR) (T_8) (2.15 %) and significantly higher than all other treatments. This was followed by BC @ 5 kg plant^{-1} + 75% NPK as per POP (T_4) (2.00 %), which was superior to the remaining treatments. BC alone 10 kg plant^{-1} (T_{11}) (1.62 %) was found with the lowest value at harvest stage.

4.3.2.4 Foliar Calcium

Foliar Ca concentration too showed appreciable variation between treatments at harvest stage (Table 32). Application of BC @ 10 kg plant^{-1} + NPK as per POP (T_3) significantly increased calcium concentration (3.33 %) as compared to all other treatments except BC @ 5 kg plant^{-1} + 75% NPK as per POP (T_4) (3.29 %) and BC @ 5 kg plant^{-1} + NPK as per POP (T_2) (3.05 %) which gave on par values. BC alone 10 kg plant^{-1} (T_{11}) recorded lowest value of 2.27 %.

4.3.2.5 Foliar Magnesium

Unlike the other essential nutrient elements, effect of various treatments at harvest stage was significant in the foliar Mg concentration (Table 32). However the foliar Mg concentration ranged between 0.14 % and 0.08 % in the various treatments. The highest Mg concentration of 0.14 % was found in the BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T_{10}) which was on par with BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR) (T_8), BC @ 5 kg plant^{-1} + 75 % (NPK + secondary & micronutrients as per STBR) (T_9) and BC @ 5 kg plant^{-1} + NPK as per POP (T_2) treatments with a value of 0.13 %. Treatment BC alone 10 kg plant^{-1} (T_{11}) observed with the lowest value 0.08 % for foliar Mg concentration in the entire study.

Table 31. Effect of biochar based treatments on foliar N, P and K concentration, %

	N	P	K
T$_1$- Package of practices recommendation	5.22 ^{d}	0.18 ^{b}	1.64 ^{gh}
T$_2$- BC @ 5 kg plant^{-1} + NPK as per POP	5.81 ^{bc}	0.20 ^{b}	1.72 ^{fgh}
T$_3$- BC @ 10 kg plant^{-1} + NPK as per POP	5.17 ^{d}	0.18 ^{a}	1.78 ^{efg}
T$_4$- BC @ 5 kg plant^{-1} + 75% NPK as per POP	6.39 ^{a}	0.31 ^{b}	2.00 ^{bc}
T$_5$- BC @ 10 kg plant^{-1} + 75% NPK as per POP	5.45 ^{cd}	0.18 ^{b}	1.95 ^{cd}
T$_6$- FYM 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	5.39 ^{cd}	0.22 ^{b}	1.90 ^{cde}
T$_7$- BC @ 5 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	5.31 ^{cd}	0.21 ^{b}	1.82 ^{def}
T$_8$- BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	6.36 ^{ab}	0.18 ^{b}	2.15 ^{ab}
T$_9$- BC @ 5 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	6.18 ^{ab}	0.21 ^{b}	1.93 ^{cde}
T$_{10}$- BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	6.40 ^{a}	0.23 ^{b}	2.24 ^{a}
T$_{11}$- BC alone 10 kg plant^{-1}	4.60 ^{e}	0.17 ^{b}	1.62 ^{h}
SEm (±)	0.26	0.03	0.07
CD (0.05)	0.55	0.07	0.15

*BC-Biochar, FYM-Farm yard manure, STBR-Soil test based recommendation; ^{a,b,c,d,e} Significant difference between treatments

Table 32. Effect of biochar based treatments on foliar Ca, Mg and S concentration, %

	Ca	Mg	S
T$_1$- Package of practices recommendation	2.73 ^{bc}	0.09 ^{e}	0.16 ^{bc}
T$_2$- BC @ 5 kg plant^{-1} + NPK as per POP	3.05 ^{ab}	0.09 ^{e}	0.15 ^{c}
T$_3$- BC @ 10 kg plant^{-1} + NPK as per POP	3.33 ^{a}	0.10 ^{de}	0.16 ^{bc}
T$_4$- BC @ 5 kg plant^{-1} + 75% NPK as per POP	3.29 ^{a}	0.11 ^{cde}	0.16 ^{bc}
T$_5$- BC @ 10 kg plant^{-1} + 75% NPK as per POP	2.77 ^{bc}	0.11 ^{cde}	0.15 ^{bc}
T$_6$- FYM 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	2.58 ^{cd}	0.12 ^{bc}	0.18 ^{abc}
T$_7$- BC @ 5 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	2.53 ^{cd}	0.12 ^{bc}	0.17 ^{bc}
T$_8$- BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	2.55 ^{cd}	0.13 ^{ab}	0.18 ^{ab}
T$_9$- BC @ 5 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	2.36 ^{d}	0.13 ^{ab}	0.17 ^{bc}
T$_{10}$- BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	2.45 ^{cd}	0.14 ^{a}	0.21 ^{a}
T$_{11}$- BC alone 10 kg plant^{-1}	2.27 ^{d}	0.08 ^{f}	0.11 ^{d}
SEm (±)	0.16	-	0.01
CD (0.05)	0.34	0.01	0.03

*BC-Biochar, FYM-Farm yard manure, STBR-Soil test based recommendation; ^{a,b,c,d,e} Significant difference between treatments

4.3.2.6 Foliar Sulphur

The pattern of foliar S concentration in the different treatments at harvest stage exhibited significant variation as is evident in Table 32. The highest concentration of 0.21 % foliar S was found in the BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T_{10}) treatment and it was found to be on par with BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR) (T_8) and FYM 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR) (T_6) with the same values of 0.18 %. The lowest concentration of 0.11 % foliar S was recorded in BC alone 10 kg plant^{-1} (T_{11}) treatment.

4.3.2.7 Foliar Iron

The values of foliar Fe concentration at final harvest stage are presented in Table 33. Application of BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T_{10}) (1053.50 mg kg^{-1}) registered significantly higher Fe concentration than all other treatments except BC @ 5 kg plant^{-1} + 75% NPK as per POP (T_4) (998 mg kg^{-1}) which was on par. This was followed by BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR) (T_8) (877.83 mg kg^{-1}) which was on par with BC @ 5 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR) (T_7) (854.50 mg kg^{-1}) and BC @ 5 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T_9) (823.16 mg kg^{-1}) which were found to be significantly higher than the remaining treatments. The lowest value of 518.33 mg kg^{-1} was recorded by the BC alone 10 kg plant^{-1} (T_{11}) treatment.

4.3.2.8 Foliar Manganese

It had been statistically observed that the treatments had significant influence on foliar Mn concentration at final harvest stage (Table 33). The highest foliar concentration of Mn was noticed in BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) (T_{10}) with 172.75 mg kg^{-1} which was on par with all the other remaining treatments except BC @ 5 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR) (T_7) and BC alone 10 kg plant^{-1} (T_{11}) which recorded values of 101.01 mg kg^{-1} and 99.26 mg kg^{-1} respectively.

Table 33. Effect of biochar based treatments on foliar Fe, Mn and Zn concentration, mg kg^{-1}

	Fe	Mn	Zn
T_1- Package of practices recommendation	654.83 ^{d}	145.65 ^{a}	14.50 ^{bc}
T_2- BC @ 5 kg plant^{-1} + NPK as per POP	709.16 ^{d}	151.38 ^{a}	11.80 ^{def}
T_3- BC @ 10 kg plant^{-1} + NPK as per POP	750.00 ^{cd}	147.40 ^{a}	11.43 ^{ef}
T_4- BC @ 5 kg plant^{-1} + 75% NPK as per POP	998.00 ^{a}	165.88 ^{a}	13.55 ^{cd}
T_5- BC @ 10 kg plant^{-1} + 75% NPK as per POP	689.83 ^{d}	157.00 ^{a}	14.58 ^{bc}
T_6- FYM 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	752.00 ^{cd}	161.66 ^{a}	15.91 ^{ab}
T_7- BC @ 5 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	854.50 ^{bc}	101.01 ^{b}	13.08 ^{cde}
T_8- BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	877.83 ^{bc}	168.18 ^{a}	11.41 ^{ef}
T_9- BC @ 5 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	823.16 ^{bc}	154.60 ^{a}	12.82 ^{cde}
T_{10}- BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	1053.50 ^{a}	172.75 ^{a}	16.58 ^{a}
T_{11}- BC alone 10 kg plant^{-1}	518.33 ^{e}	99.26 ^{b}	10.73 ^{f}
SEm (±)	52.78	16.22	0.94
CD (0.05)	110.10	33.85	1.98

*BC-Biochar, FYM-Farm yard manure, STBR-Soil test based recommendation; ^{a,b,c,d,e} Significant difference between treatments

Table 34. Effect of biochar based treatments on foliar Cu and B concentration, mg kg^{-1}

	Cu	B
T_1- Package of practices recommendation	5.98	40.45
T_2- BC @ 5 kg plant^{-1} + NPK as per POP	6.35	54.52
T_3- BC @ 10 kg plant^{-1} + NPK as per POP	5.70	59.69
T_4- BC @ 5 kg plant^{-1} + 75% NPK as per POP	6.38	58.62
T_5- BC @ 10 kg plant^{-1} + 75% NPK as per POP	6.24	54.17
T_6- FYM 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	6.61	51.49
T_7- BC @ 5 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	6.48	51.49
T_8- BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	7.25	52.92
T_9- BC @ 5 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	5.01	46.82
T_{10}- BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	6.16	53.28
T_{11}- BC alone 10 kg plant^{-1}	4.21	38.66
SEm (±)	2.96	6.45
CD (0.05)	NS	NS

*BC-Biochar, FYM-Farm yard manure, STBR-Soil test based recommendation

4.3.2.9 Foliar Zinc

There was significant difference between treatments in the foliar concentration of Zn at harvest stage as presented in Table 33. The highest foliar Zn concentration of 16.58 mg kg^{-1} was found in the treatment BC @ 10 kg $plant^{-1}$ + 75% (NPK + secondary & micronutrients as per STBR) (T_{10}) and it was on par with FYM 10 kg $plant^{-1}$ + (NPK + secondary & micronutrients as per STBR) (T_6) with a value of 15.91 mg kg^{-1}. The lowest concentration was observed for BC alone 10 kg $plant^{-1}$ (T_{11}) (10.73 mg kg^{-1}).

4.3.2.10 Foliar Copper

The results of foliar Cu concentration at harvest stage as presented in Table 34. The foliar concentration of Cu ranged from 7.25 mg kg^{-1} (BC @ 10 kg $plant^{-1}$ + (NPK + secondary & micronutrients as per STBR) (T_8) to 4.21 mg kg^{-1} (BC alone 10 kg $plant^{-1}$) (T_{11}). There was no significant difference between the treatments with respect to foliar Cu concentration at harvest stage.

4.3.2.11 Foliar Boron

The analytical results of foliar B concentration with respect to various treatments are presented in Table 34. The foliar concentration of B ranged from 59.69 mg kg^{-1} (BC @ 10 kg $plant^{-1}$ + NPK as per POP) to 38.66 mg kg^{-1} (BC alone 10 kg $plant^{-1}$). There was no significant difference between the treatments with respect to foliar B concentration.

4.3.3 Effect of Treatments on Nutrient Use Efficiency

The results of nutrient use efficiency presented in the Table 35. The highest nutrient use efficiency of 50.4 % was recorded in the BC @ 10 kg $plant^{-1}$ + 75% (NPK + secondary & micronutrients as per STBR) (T_{10}), followed by BC @ 5 kg $plant^{-1}$ + 75% NPK as per POP (T_4) with a value of 31.07 %.

Table 35. Effect of treatments on nutrient use efficiency (NUE), %

	Nutrient use efficiency (%)
T_1- Package of practices recommendation	0
T_2- BC @ 5 kg plant^{-1} + NPK as per POP	13.04
T_3- BC @ 10 kg plant^{-1} + NPK as per POP	11.11
T_4- BC @ 5 kg plant^{-1} + 75% NPK as per POP	31.07
T_5- BC @ 10 kg plant^{-1} + 75% NPK as per POP	9.98
T_6- FYM 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	18.35
T_7- BC @ 5 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	2.41
T_8- BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	13.04
T_9- BC @ 5 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	25.28
T_{10}- BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	50.40
T_{11}- BC alone 10 kg plant^{-1}	0

*BC-Biochar, FYM-Farm yard manure, STBR-Soil test based recommendation

4.3.4 Correlation Study

4.3.4.1 Yield with Soil Physical, Chemical and biological Characteristics

Correlation of yield with soil physical, chemical and biological characteristics presented in the Table 36. Yield was significantly correlated with bulk density, porosity, soil pH, CEC, OC, available N, K, Mg, S, Zn and B. Bulk density negatively correlated with porosity, OC, CEC, available N, K, Mg, Zn, B and dehydrogenase activity.

4.3.4.2 Growth Characters with Yield and Yield attributes

Correlation studies revealed that the bunch weight was significantly and positively correlated with plant height, pseudostem girth, number leaves, dry matter production, number of hands bunch^{-1}, number of fingers bunch^{-1} and length and girth of index finger. The girth of pseudostem was positively correlated with dry matter production, number of hands bunch^{-1}, number of fingers bunch^{-1} and length and girth of index finger (Table 37).

4.3.5 Cost of Biochar Production

Cost of biochar production details presented in Table 38. Fabrication and design cost of micro biochar kiln unit was Rs. 25300/- and biochar production cost including transportation, grinding and sieving was 10340 Rs t^{-1}. Overall biochar production cost was Rs.10 kg^{-1}.

4.3.6 Economic Analysis

Details regarding the economic analysis are presented in Table 39. The BC @ 10 kg $plant^{-1}$ + 75 % (NPK + secondary & micronutrients as per STBR) (T_{10}) treatment registered the highest gross income (1188200 Rs ha^{-1}), net returns (689336.25 Rs ha^{-1}) and B:C ratio (2.38) compared to all other treatments.

4.3.7 Biochar Based Nutrient Mix for Nendran Banana

Based on best treatment, biochar @ 10 kg $plant^{-1}$ + 75% (NPK + secondary & micronutrients as per STBR) (T_{10}) prepared biochar based nutrient mix, composition was formulated with 10 kg biochar along with urea $_{260.21g}$, MOP $_{528.75g}$ and $MgSO_4$ $_{23.44g}$ for Loamy, Kaolinitic, Isohyperthermic, Typic Kandiustults of Vellayani series. Nutrient mix had an alkaline pH of 7.65 and EC of 0.71 dSm^{-1}.

Plate 15. Biochar based nutrient mix for nendran banana

Table 36. Correlation of yield with soil physical, chemical and biological parameters

	Yield	WHC	BD	Porosity	pH	CEC	OC	N	P	K	Ca	Mg	S	Zn	B	Dehydrogenase
Yield	1	ns	-0.482**	0.654**	0.399*	0.381*	0.728**	0.701**	ns	0.629**	ns	0.552**	0.468**	0.680**	0.636**	ns
WHC		1	-0.436*	ns	0.590**	0.624**	ns	ns	ns	ns	ns	0.426*	Ns	ns	0.430*	0.604**
BD			1	-0.681**	-0.694**	-0.460**	-0.495**	-0.457**	ns	-0.704**	ns	-0.554**	Ns	-0.422*	-0.596**	0-.635**
Porosity				1	0.596**	0.527**	0.639**	0.573**	ns	0.654**	ns	0.600**	0.449**	0.575**	0.511**	0.453**
pH					1	0.684**	ns	ns	ns	0.521**	ns	0.493**	Ns	0.597**	0.506**	0.683**
CEC						1	ns	ns	ns	ns	ns	0.450**	Ns	0.623**	0.529**	0.599**
OC							1	0.619**	ns	0.692**	ns	0.687**	0.620**	0.508**	0.586**	ns
N								1	.536**	0.847**	ns	0.651**	0.611**	0.562**	0.527**	ns
P									1	0.438*	0.745**	0.360*	0.358*	ns	ns	ns
K										1	ns	0.737**	0.644**	0.566**	0.712**	0.399*
Ca											1	ns	Ns	ns	ns	ns
Mg												1	0.566**	0.512**	0.648**	0.508**
S													1	0.380*	ns	ns
Zn														1	0.643**	0.464**
B															1	0.603**
Dehydrogenase																1

** and * significant at $p < 0.01$ and 0.05; n.s. not significant

Table 37. Correlation of growth characters with yield and yield attributes

	Weight of bunch	Plant height	Pseudostem Girth	Number of leaves	Dry matter production	Number of hands bunch^{-1}	Number of fingers bunch^{-1}	Length of index finger	Girth of index finger
Weight of bunch	1	0.827**	0.570**	0.550**	0.842**	0.492**	0.490**	.842**	0.717**
Plant height		1	0.651**	0.495**	0.797**	0.465**	0.505**	0.797**	0.632**
Pseudostem Girth			1	ns	0.594**	0.600**	0.622**	0.525**	0.655**
Number of leaves				1	0.509**	ns	ns	0.448**	0.452**
Dry matter production					1	0.555**	0.521**	0.798**	0.790**
Number of hands bunch^{-1}						1	0.759**	.460**	0.706**
Number of fingers bunch^{-1}							1	ns	0.591**
Length of index finger								1	0.694**
Girth of index finger									1

** and * significant at $p < 0.01$ and 0.05; n.s. not significant

Table 38. Cost of biochar production

Particulars	
Initial cost	
Biochar production micro kiln	25300/-
Recurring cost	
Labour cost (Rs t^{-1})	
Production of biochar	9340/-
Grinding and sieving	
Transportation	1000/-
Total cost	10340/-

Table 39. Effect of treatments on gross income, net returns and B:C ratio of the treatments

Treatments	Gross income (Rs ha^{-1})	Net returns (Rs ha^{-1})	B:C ratio
T_1- Package of practices recommendation	807300	191235.00	1.31
T_2- BC @ 5 kg plant^{-1} + NPK as per POP	912600	286535.00	1.46
T_3- BC @ 10 kg plant^{-1} + NPK as per POP	897000	405115.45	1.82
T_4- BC @ 5 kg plant^{-1} + 75% NPK as per POP	1058200	556684.50	2.11
T_5- BC @ 10 kg plant^{-1} + 75% NPK as per POP	887900	392458.45	1.79
T_6- FYM 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	955500	484140.00	2.03
T_7- BC @ 5 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	826800	402940.00	1.95
T_8- BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	912600	441240.00	1.94
T_9- BC @ 5 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	1011400	501136.25	1.98
T_{10}- BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	1188200	689336.25	2.38
T_{11}- BC alone 10 kg plant^{-1}	707200	153500.00	1.28

*BC-Biochar, FYM-Farm yard manure, STBR-Soil test based recommendation

DISCUSSION

5. DISCUSSION

The results generated from the study on 'Technology refinement for biochar production and evaluation of its effect on soil health and crop productivity' are discussed hereunder. Biochar from tender coconut husk is considered as good soil amendment and nutrient source.

5.1 REFINEMENT OF BIOCHAR PRODUCTION TECHNOLOGY

The previous biochar model consists of a single barrel reactor with chimney for synags exhaustion. A modified prototype of micro biochar kiln was designed and fabricated for the pyrolysis of biochar from tender coconut husk. This newly designed apparatus got high efficiency of production of biochar and with provision for syngas collection.

5.1.1 Design and Fabrication of the Modified Micro Biochar Kiln

The prototype biochar kiln has a double barrelled reactor assembly which could effectively build, supply, maintained and regulate the ideal temperature conditions required for the pyrolytic process. It is well established that the reactor temperature, particle heating rate and solid residence time are the key factors influencing the char yield during pyrolysis (Kan *et al* 2016; Kumar and Chandrashekar, 2013). The temperature supply to the biomass feeder barrel could be effectively done by an indirect and constant transmission of heat energy from the source located at the bottom of the outer barrel so as to create the optimum temperature required for pyrolysis. It could overcome the discrepancy in the previous prototype in which the direct supply of heat led to excessive charring of the biomass substrate and enhanced syngas production, thus decreasing pyrolytic efficiency. Heating rate variation could influence the properties of the char produced by influencing the pyrolysis mechanisms and changing the amount of time spent at various temperature points (Angin, 2013; Mundike *et al*, 2017). Thus a better heating rate optimisation could be achieved in the refined micro biochar kiln. Another major determinant of pyrolytic efficiency is the maintenance of zero or limited oxygen environment (Mohan *et al.*, 2016). The double barrelled micro kiln designed with sparse perforations enabled the limited oxygen environment requisite for efficient pyrolysis which had largely remained insatiable in the single barrelled basic prototype unit fabricated earlier. Kan *etal.* (2016) opines that though biomass pyrolysis is by and large done in an inert environment, slightly oxidising atmospheres is more beneficial. Yet another added advantages of the refined prototype is the provision for monitoring of temperature build up, maintenance and regulation in the reactor unit by means of a digital infrared thermometer. Moreover the refined prototype unit is equipped with a cooling assembly system which facilitates collection of the syngas produced as a by-product during pyrolysis. The overall refinement employing these technologies in the modified low cost micro biochar unit resulted in efficient pyrolysis of tender coconut husk biomass. This is evidenced from the increased recovery percentage of 50 % as compared to the recovery percentage of 33 % in the basic prototype biochar unit developed initially.

5.1.2 Biochar Production from Tender Coconut Husk Biomass

The tender coconut husk biomass barrel of the low cost, modified micro biochar kiln had a substrate capacity of 30 kg which enabled the best option for disposal of lignocellulosic waste at the source of origin itself, thus promoting waste disposal at source. The process of pyrolysis in the reactor unit commenced as the supply of heat advanced in gradual progression and attained a temperature regime of 350 °C. It took about 30 minutes to reach this condition (Fig. 3). This temperature was then maintained for 60 minutes. The hold time of pyrolysis was 60 minutes during which the lignocellulosic biomass was held isothermally and a subsequent cooling down of the reactor determined the biochar yield. Mandal *et al.* (2013) and Xiong *et al.* (2014) have reported similar ‘baking’ time for pyrolysis of lignocellulosic samples.

Pyrolysis of biomass primarily consists of three stages *viz.*, initial evaporation of free moisture, primary decomposition and secondary reactions that involve oil cracking and repolymerisation (White *et al.*, 2011). In pyrolysis process lignocellulosic biomass materials decompose on heating or exposure to an ignition source by two alternative pathways. The first pathway, which dominates at temperatures below 300°C, involves reduction in the degree of polymerization by bond scission; elimination of water; formation of free radicals, carbonyl, carboxyl, and hydroperoxide groups; evolution of CO and CO_2 and finally, production of a highly reactive carbonaceous biochar. The second pathway, which takes over at temperatures above 350 °C, involves cleavage of molecules by transglycosylation, fission, and disproportionation reactions to provide a mixture of tarry anhydro sugars and lower molecular weight volatile products (Shafizadeh, 2014). The reaction pathway of cellulose pyrolysis is described as Waterloo-mechanism represented in Fig. 4 (Boukis, 1997). Biomass decomposition to solid char primarily takes place at 200-400 °C which is responsible for the largest degradation of biomass (Fisher *et al.*, 2002).

At the end of the process of pyrolysis, tender coconut husk transformed into a solid residue of biochar, their gaseous components (syngas) and little ash, where cellulose and lignin are broken down from aliphatic carbon structure to aromatic structure. Because of its aromatic structure dominated by aromatic carbon, biochar has been found to be biochemically recalcitrant as compared to uncharred organic matter. This technology can be used for producing biochar from any dry biomass.

5.1.3 Biochar Characterization

Analysis of chemical parameters of the biochar revealed the innate alkalinity of the synthesized biochar with a mean pH of 8.53 and a comparatively lower EC of 1.70 dS m^{-1} at 25 °C. 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). Shenbagavalli and Mahimairaja (2012) reported identical values for coconut shell biochar. Kumari *et al.* (2017) observed similar values for pH and EC which had the potential for biochar induced short term changes on application as soil amendment rather than long term effects. Hence there is a prospect of biochar being considered as a good soil ameliorant (Dainy, 2015) for enhancement of soil pH in the predominantly acidic soils of Kerala.

The biochar showed a CEC of 15.26 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. Biochar produced above 350 °C are dominated by aromatic C groups and a range of different functional groups exists 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 in adsorbing 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 its 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. Because of high CEC exhibited by the biochar produced from tender coconut husk, it is a good adsorber of all the cations and hence soil addition of biochar reduces the nutrient losses by leaching.

Biochar samples from pyrolysis of tender coconut husk resulted in a comparatively higher AEC of 5.64 cmol kg^{-1}. Lawrinenko and Laird (2015) concluded that oxonium functional groups contribute pH independent AEC and that both pyridinic functional groups and non-specific proton adsorption by condensed aromatic rings contribute pH dependent AEC to biochar. AEC of biochar produced from four feedstocks (maize stover, cellulose, alfalfa meal and albumin) increased with decreasing pH and peak pyrolysis temperature. A cellulose biochar, composed almost entirely of C, H, and O, exhibited significant AEC at pH 8 suggesting that pH independent O containing functional groups contribute to the high AEC of biochar synthesized (Lawrinenko and Laird, 2015). Since AEC of produced biochar is high, it can adsorb anions like NO_3^-, $H_2PO_4^-$, HPO_4^{2-}, SO_4^{2-} and BO_3^{3-} which will lead to reduction in losses.

The total organic carbon content was 70.1 %. The pyrolysis of biochar from the tender coconut husk biomass does not seem to result in excessive evolution of CO_2, a potent greenhouse gas to the atmosphere. The very high content of total organic carbon content (70.10 %) which mainly comprises, conjugated aromatic compounds of six C atoms linked together in rings. The condensed aromatic nature of biochar is responsible for its stability in the environment. The biochar structure is essentially amorphous, but may contain crystalline structures locally of highly ordered graphene sheets (Downie *et al.,* 2009). Moreover soil application of this biochar would serve to supplement the soil carbon pool thus definitely contributing to carbon sequestration.

The kind of feedstock and the conditions of pyrolysis are the twin major factors that determine the nutrient composition of biochar whereas the availability of the nutrients is largely determined by the adsorptive capacity of biochar (Siddique *et al*., 2016). The biochar produced contained N (1.52 %), P (0.40 %), K (2.26 %), Ca (0.54 %), Mg (0.46 %), S (0.27 %), Fe (89.9 mg kg^{-1}), Mn (2.84 mg kg^{-1}) and B (6.78 mg kg^{-1}) respectively. Contents of major nutrients N, P and K, secondary nutrients Ca, Mg and S were comparable with the nutrient contents of biochar produced from various substrates such as sugarcane bagasse, cocoa peat, palm kernel shell under varying conditions of pyrolysis (Githinji, 2014; Lee *et al*., 2013; Liu and Balasubramanian, 2014). The biochar contained substantial quantities of micronutrients like Fe, Mn, Zn, Cu and B, comparable to that of organic manures from various sources. Thus, the biochar synthesized from tender coconut husk biomass under set pyrolytic conditions in the biochar micro kiln was found to be a good source of all the essential nutrients.

The basic structure of biochar comprises of aromatic rings of six carbon atoms without oxygen and hydrogen (Siddiqui *et al.*, 2016). The nutrient ratios exhibited by biochar from tender coconut husk were C:N (46.11), C:P (175.25), C:S (259.62) and C:N:P:S (350:7.5:2:1) respectively (Fig. 5). Hamdani *et al.*, 2017 and Shenbagavalli and Mahimairaja, 2012 reported that coconut shell and coir waste biochar had C:N ratio of 96.8 and 89.4.

The concentration of the heavy metals Pb, Cd, Ni, Cr, Zn and Cu in the tender coconut husk biochar were much below the maximum allowable threshold levels prescribed by IBI (2014). Hence biochar from tender coconut husk is safe for use as a soil amendment. Hence biochar application will not cause heavy metal pollution or human toxicity and is environmentally safe to use. Moreover, a negative charge build up on the biochar surface, a unique characteristic of biochar renders an extra sorption ability towards positively charged metal contaminants inclusive of heavy metals, thereby preventing ground water contamination (Delwiche *et al.*, 2014; Nagodavithane *et al.*, 2014). This probably would lead to explore the possibility of utilizing biomass biochar as a bioremediator.

It is evident from the experiment, biochar synthesized from tender coconut husk, a lignocellulose biowaste has ideal chemical properties that qualify it to be used as a prospective agricultural soil amendment which has ameliorative properties, maintains soil bio physicochemical quality, mitigate nutrient leaching and groundwater contamination. It is environmentally safe, supplements to soil carbon pool and favours soil carbon sequestration.

5.1.4 Syngas Analysis

The syngas produced during pyrolysis was analysed by gas chromatography and its composition was identified as methane (22.89%), carbon dioxide (67.70%), oxygen (8.74%), hydrogen (0.66%) and n-Butane (0.001%) respectively on normal mol dry (%) basis (Fig. 6). As a basic constituents of pyrolysis gas, CO_2 emanate from the decomposition and reforming of carbonyl (C=O) and carboxyl (COO) groups (Qu *et al.*, 2011). The appreciable presence of CH_4, a light hydrocarbon may be ascribed to the decomposition of weakly bonded methoxyl ($-O-CH_3$) and methylene ($-CH_2-$) groups and also to the secondary level decomposition of the oxygenated compounds (Uddin *et al.* 2011). Presence of H_2 is indicative of the secondary decomposition and reformation of aromatic C=C and C-H groups at enhanced temperatures (Liu *et al.,* 2008). Carbon monoxide and nitrogen were below detectable levels. Since recovery percentage of solid biochar is comparatively more, the proportion of syngas produced was not in appreciable quantity when compared to the previous biochar production unit. The composition of syngas produced revealed that it does not hold a prospect of being used as a bioenergy source. However, the prospective potential of separation and utilization of the constituent gases in syngas collected needs in depth study. The utilization of the major component, carbon dioxide gas in physiological studies at elevated concentration environments could be further explored. Further there is a possibility for separation of methane gas and its utilization as energy source. There is no production of bio oil during pyrolysis. The relatively higher proportion of solid biochar formed is attributable to the higher lignin content of the tender coconut husk biomass. Akhtar *et al.* 2012 opines that while cellulose and hemicellulose rich biomass pyrolysis result in substantial bio oil production, lignin rich biomass pyrolysis give a larger proportion of solid char. All these qualities attribute this refined technology as the most effective in carbon sequestration and safe waste management. Lee *et al.* (2017) reported that the syngas contains a mixture of four primary constitutes: hydrogen (20 %), carbon dioxide (50%), nitrogen (15 %) and methane (5 %).

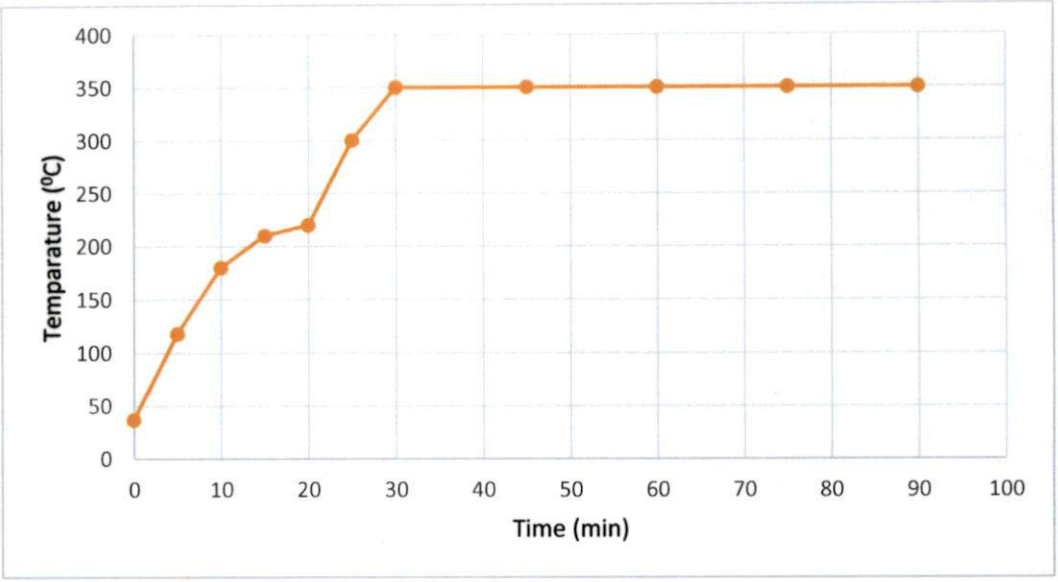


Fig. 3. Temperature build up within the reactor unit of the micro biochar kiln

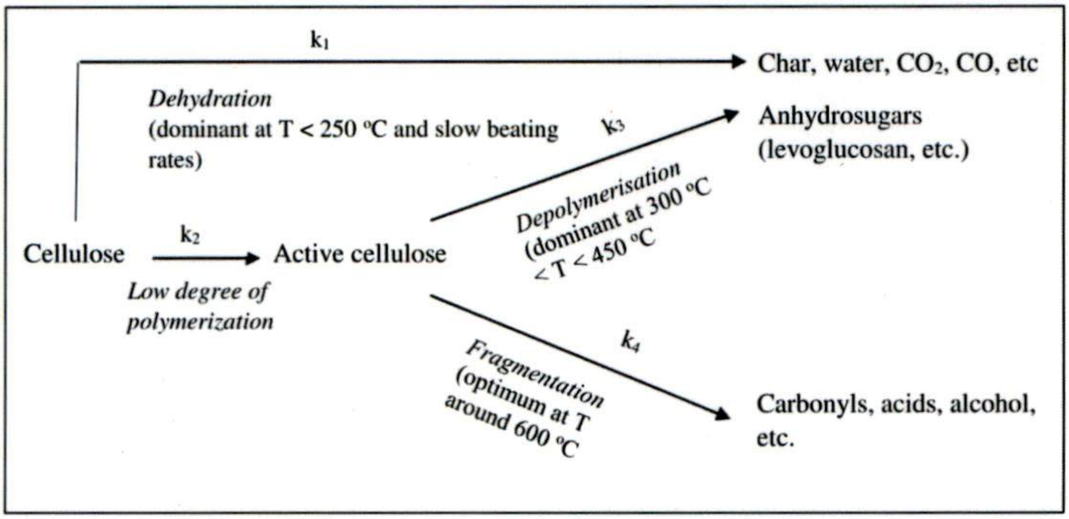


Fig. 4. Waterloo-mechanism of primary decomposition of cellulose (Boukis, 1997)

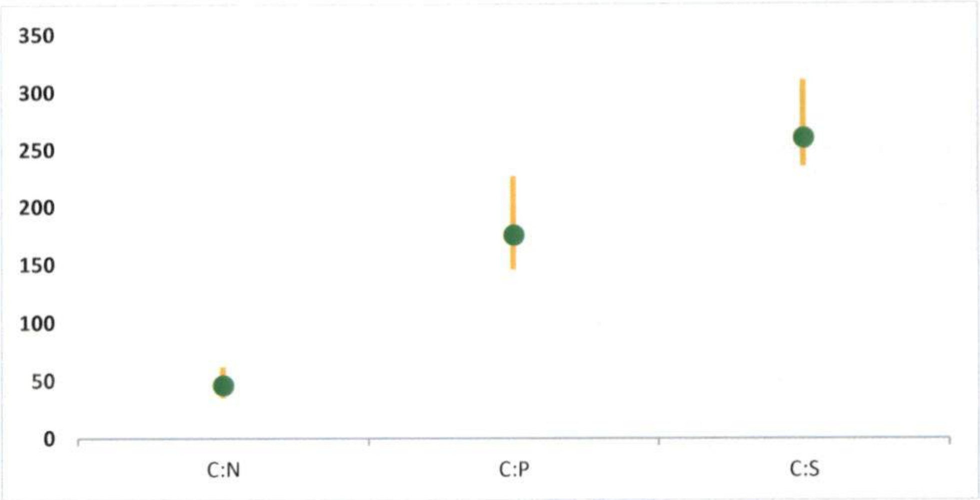


Fig. 5. Fertility indices of biochar in terms of C:N, C:P and C:S ratios. Error bars indicate standard deviation from the mean (n =3)

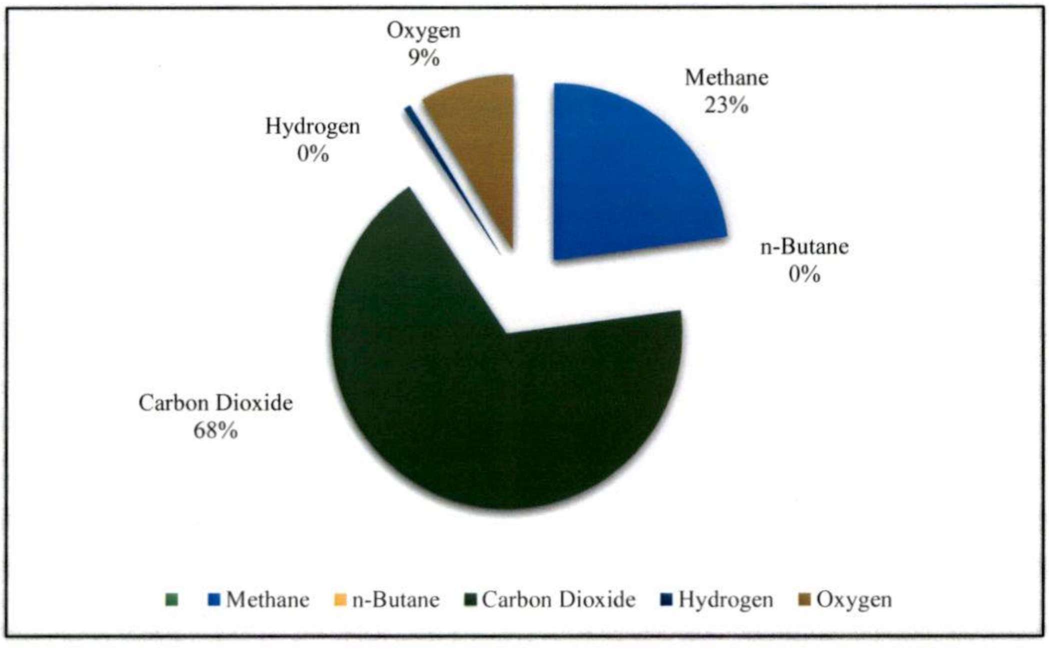


Fig. 6. Syngas composition during pyrolysis of tender coconut husk (dry normal mol %)

5.2 FIELD EXPERIMENT FOR EVALUATION OF BIOCHAR ON SOIL HEALTH, YIELD AND QUALITY OF BANANA

The salient results of the field experiment conducted to study the effect of biochar on soil health and crop productivity using banana as test crop are discussed in this session.

5.2.1 Effect of Biochar on Soil Fertility Parameters

5.2.1.1 Effect of Treatments on Physical properties of soil

The physical properties of the soil were significantly influenced by the application of treatments.

5.2.1.1.1 Water Holding Capacity (WHC)

Different treatments significantly influenced the WHC of soil at final harvest stage. An increase in the WHC from 24.3 % to 38.18 % was observed by the application of biochar @ 10 kg plant^{-1} + 75% as per STBR (T_{10}) (Fig. 7). Biochar application can influence soil porosity and thereby enhance soil water retention by 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 (Hardie *et al.*, 2014). Biochar is predicted to increase the WHC of soil owing to the enhancement in the extent of surface area by the biochar particle, consequent to which more water molecules can be stored within its porous structure (Lehmann *et al.*, 2003). The biochar produced from tender coconut husk recorded the 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^2 g^{-1} (Dainy, 2015). The surface area and microporosity of biochar are very important physical characteristics, which are positively related to the capacity of biochar 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. Application of biochar at the rate of 5 t ha^{-1} increased WHC by 2.5 % in sandy loam textured surface soil (Pandian *et al.*, 2016). 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 in the WHC was increased from 11.3 per cent for untreated control soil to 15.5 % in soils treated with rice husk biochar. An increase in the WHC of the soil has a consequential positive influence on the availability of water and essential nutrients in the soil.

5.2.1.1.2 Bulk Density

Application of biochar had a beneficial effect on reducing the bulk density of the soil. It was observed that there occurred a decrease in the bulk density of soil by 7.31 %, with application of biochar @ 10 kg plant^{-1} + 75% STBR (T_{10}) at final harvest stage (Fig. 8). The density of biochar is much lower than mineral soil of the experimental site. Hence, incorporation of biochar could increase the soil volume surface area and porosity thereby reducing the bulk density of the soil. Castellini *et al.* (2015) 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. Pandian *et al.* (2016) reported that the biochar amendment at the rate of 5 t ha^{-1} reduced the bulk density from 1.41 to 1.36 Mg m^{-3} in medium textured soil. 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).

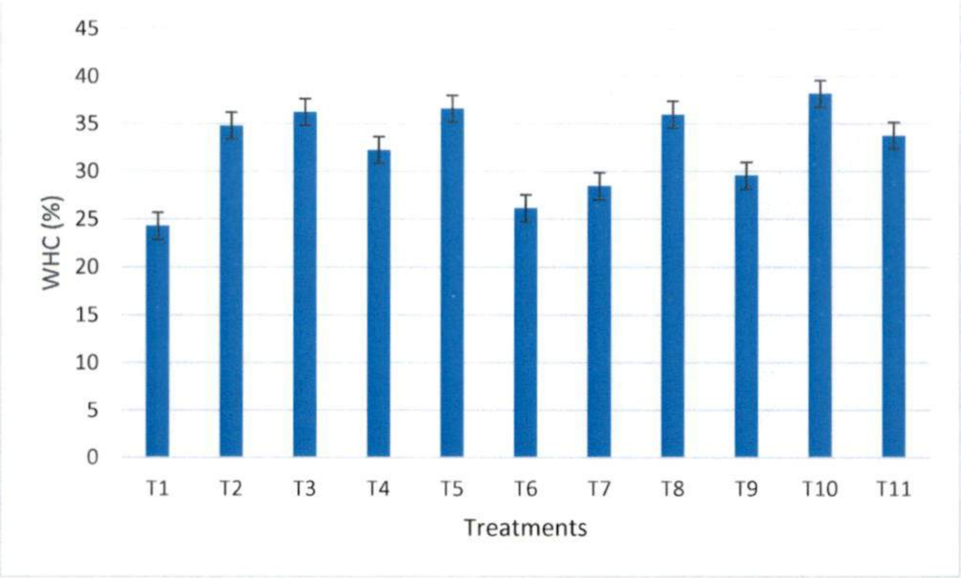


Fig. 7. Effect of treatments on soil water holding capacity at harvest stage

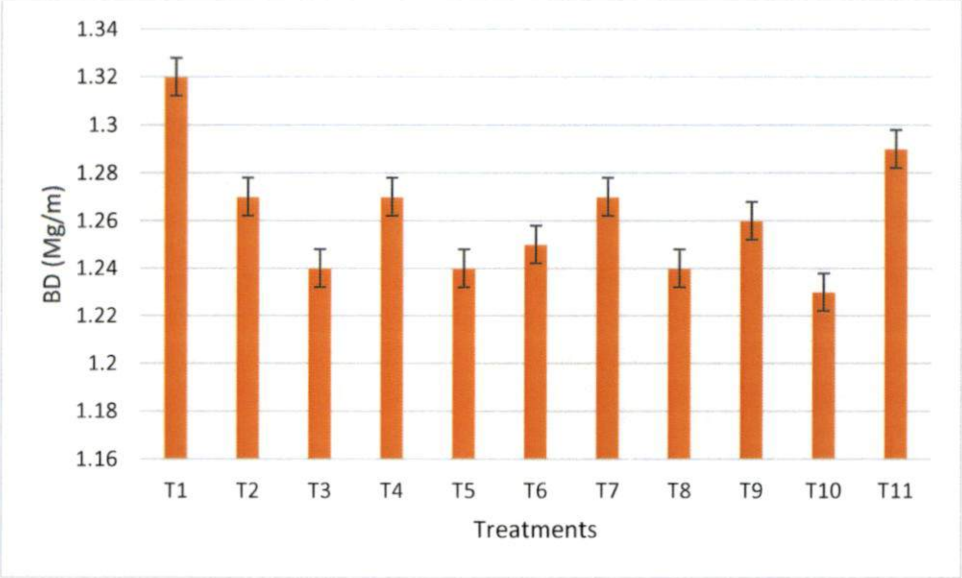


Fig. 8. Effect of treatments on soil bulk density at harvest stage

126

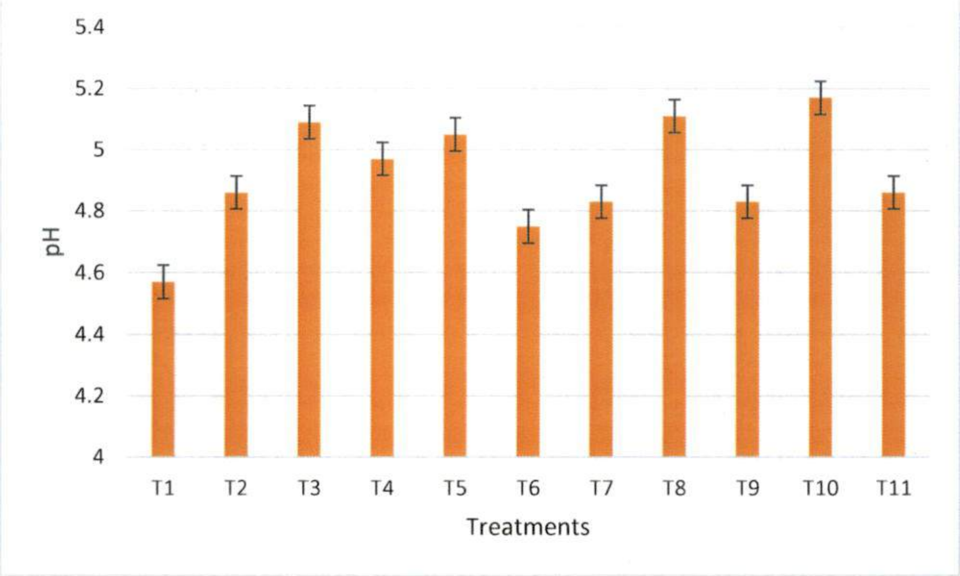


Fig. 9. Effect of treatments on soil pH at harvest stage

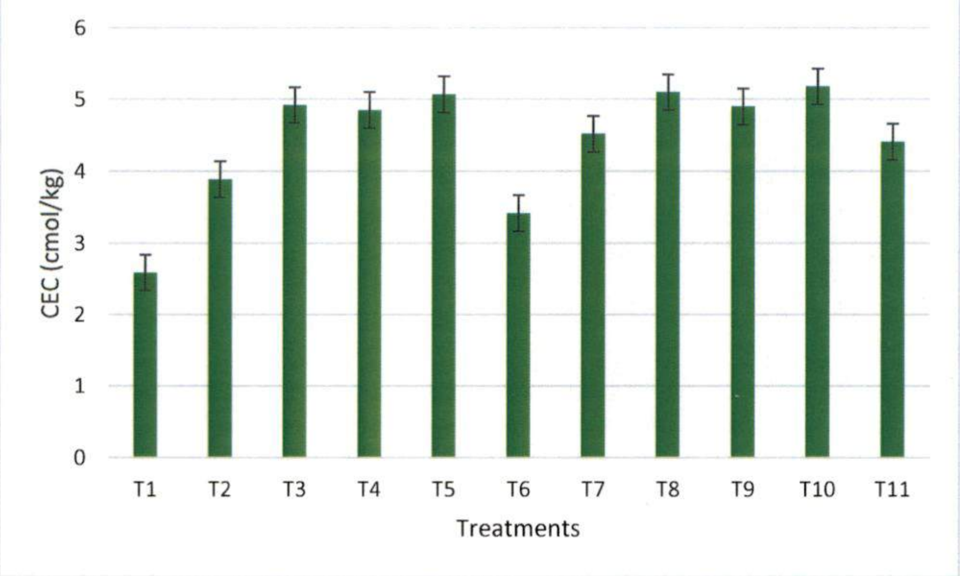


Fig. 10. Effect of treatments on soil cation exchange capacity at harvest stage

5.2.1.1.3 Porosity

Regarding porosity of the soil, application of biochar @ 10 kg plant^{-1} + 75% (NPK + secondary and micronutrients as per STBR) (T_{10}) significantly increased soil porosity by 35.32 % at final harvest stage. During pyrolysis, loss of feedstock mass in the form of volatile organic compounds levels 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, 2-5 nm, and above 5 nm, respectively (Downie et al., 2009). Mainly, the micropores are formed during pyrolysis due to loss of water molecules during dihydroxylation of the biomass. In medium textured soil, biochar application at the rate of 5 t ha^{-1} increased total soil porosity by 3% (Pandian *et al*., 2016). Application of biochar to infertile soils decreases soil bulk density and increases total pore volume (Wabel *et al*., 2013).

5.2.1.2 Effect of Treatments on Electro-Chemical and Chemical Properties of Soil

5.2.1.2.1 pH

Being 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. The initial pH of the soil of the experimental site was 4.73. The treatments, biochar @ 10 kg plant^{-1} + 75 % (NPK + secondary and micronutrients as per STBR) increased soil pH to 5.17 at final harvest stage. There was an enhancement in soil pH by 0.6 units with application of biochar when compared with package of practices recommendation (Table 40) (Fig. 9). This study is also in conformity with several other studies where biochar application increased the soil pH of acidic soils (Chintala *et al*., 2014). Steiner *et al*. (2007) reported increased concentration of alkaline metal (Ca^{2+}, Mg^{2+} and K^+) oxides present in biochar and a reduced concentration of soluble soil Al^{3+} where the positive reasons for such effects. Pandian *et al*. (2016) observed that application of *prosopis* biochar 5 t ha^{-1} raised soil pH from 5.7 to 6.3. This increase in soil pH in the biochar applied soil is primarily due to the alkaline pH (8.4 - 10.8) of biochar. Nigussie *et al.* (2012) concluded that the highest soil pH (5.44) was observed in soils treated with 10 t ha^{-1} biochar.

Depending on the biochar biomass used, basic cations such as Ca^{2+}, Mg^{2+}, K^+ and Si^{4+} 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 the authors on pecan shell derived biochar revealed that there was a high concentration of calcium oxide in the biochar, which neutralises soil acidity as follows.

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

Sparks (2003) reported that the reaction describes the reduction in exchangeable acidity whereby Ca replace 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 (2 $Al(OH)_3$).

5.2.1.2.2 Electrical Conductivity (EC)

The total soluble salt concentration decreased in all the treatments when compared to the initial EC value of 0.71 dS m^{-1}. A comparison of the different treatments revealed that the treatment which received package of practices recommendation recorded the lowest value of 0.088 dS m^{-1} and the treatment T_{10} recorded the highest value of 0.212 dS m^{-1}. A decrease in EC when compared to initial value is due to the ability of biochar in promoting the uptake of cations and anions by the crop during the entire growth period. All the soil EC values are below the tolerable limits even for the sensitive crops.

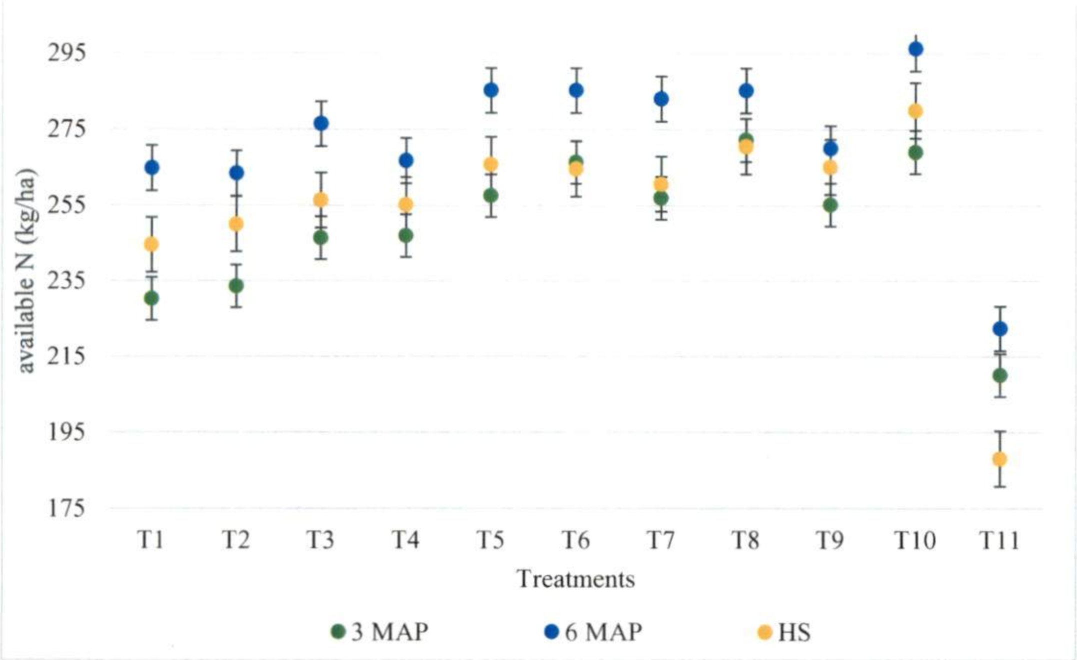


Fig. 11. Effect of treatments on soil available N at different stages

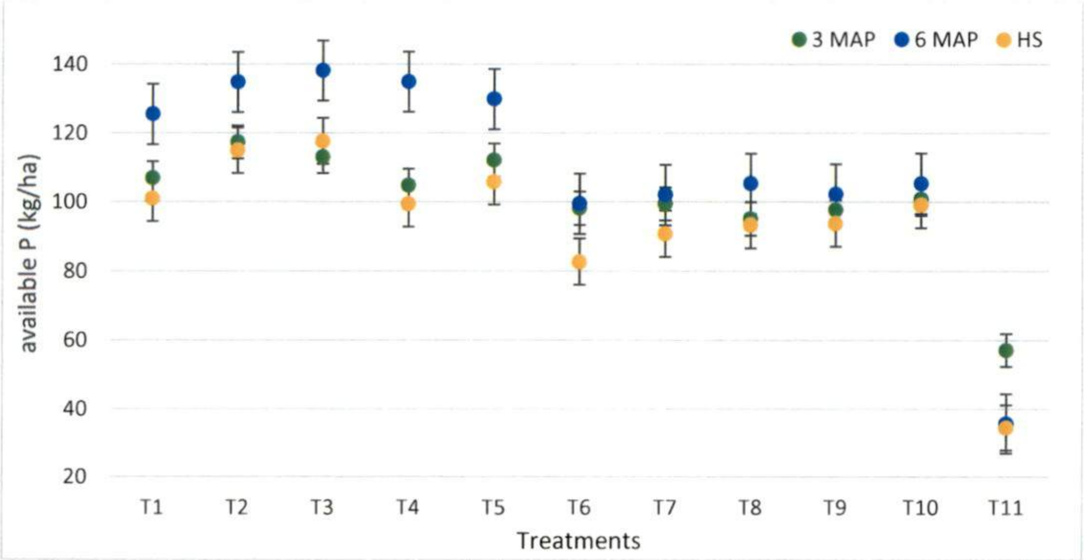


Fig. 12. Effect of treatments on soil available P at different stages

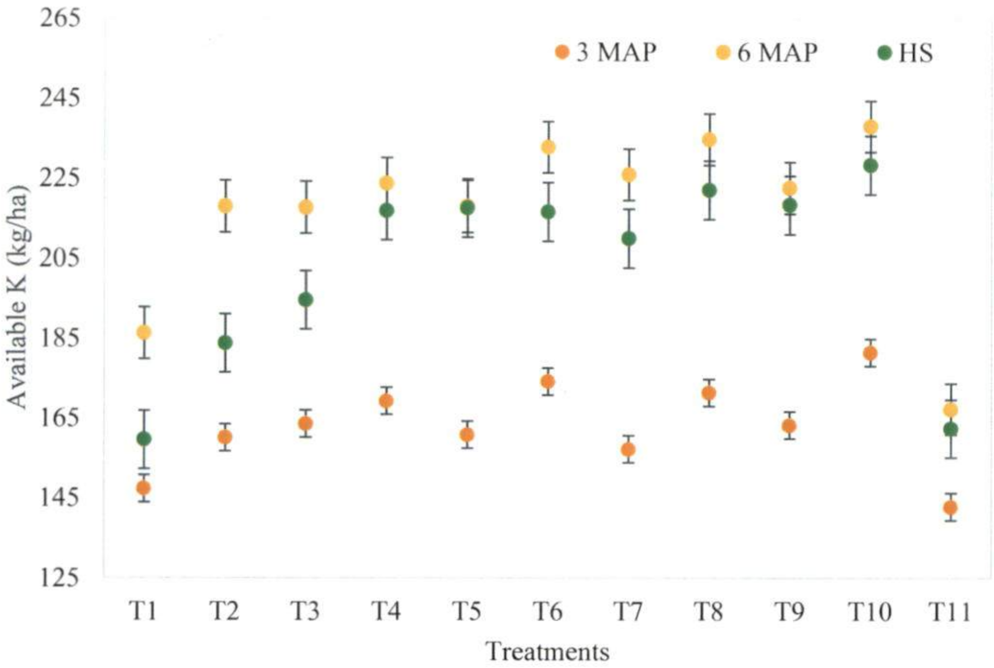


Fig. 13. Effect of treatments on soil available K at different stages

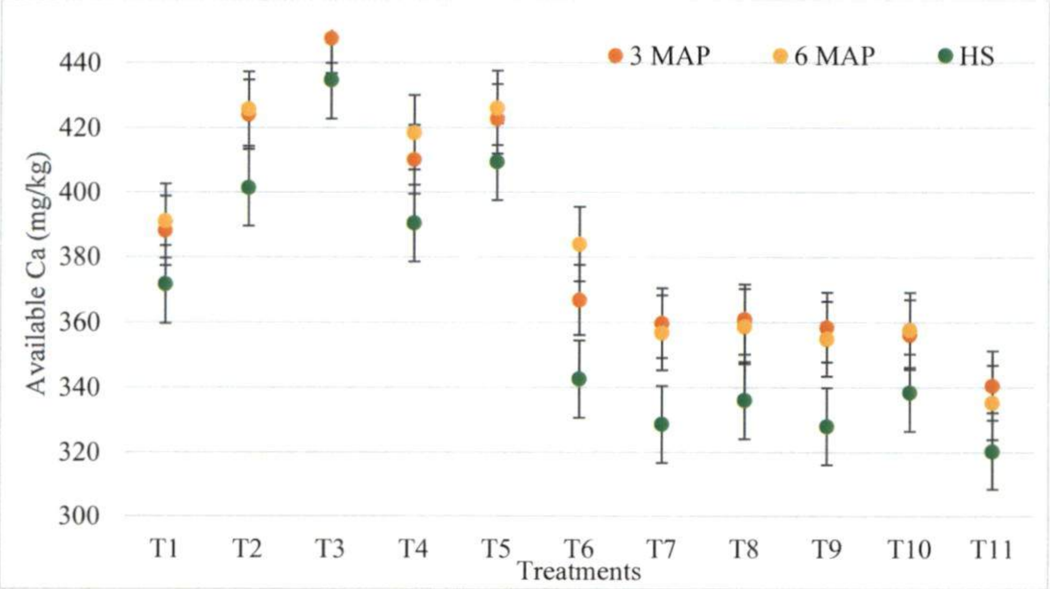


Fig. 14. Effect of treatments on soil available Ca at different stages

5.2.1.2.3 Cation Exchange Capacity (CEC)

In the biochar application treatments, a significant increase in soil CEC at final harvest stage was observed. Application of biochar @10 kg plant^{-1} + 75% (NPK + secondary and micronutrients as per STBR) (T_{10}), registered a significantly superior value of 5.18 cmol kg^{-1} (Fig. 10) when compared to the POP treatment. Increase in CEC by 100% with application of biochar can be attributed to the high specific surface area of biochar imparted by its porous structure and reactive functional groups. The high reactivity of the surfaces of the biochar particles is partly attributed to the presence of a range of reactive functional groups Si-O-Si, OH, COOH, C=O, C-O, N-H, some of which are pH-dependent (Agegnehu *et al.* 2017). These functional groups are major sites for pH-dependent charges, thereby increasing the actual CEC of biochar, which in turn increased the CEC of the amended soil. Pandian *et al.* (2016) observed that the application of red gram biochar 10 t ha^{-1} increased the cation exchange capacity to the tune of 1.4 cmol^{+} kg^{-1} and enhanced the carbon build up to 4.4 t ha^{-1}. Increase in CEC up to 40 per cent over the initial CEC by addition of biochar was reported by Topoliantz (2002). Yield improvement due to biochar application together with mineral fertilizer, also probably due to increased CEC (Lehmann *et al.* 2009)

5.2.1.2.4 Organic Carbon

The highest soil organic carbon content was observed in the treatment which received biochar @ 10 kg plant^{-1} + 75% as per STBR application (T_{10}). When compared to package of practices recommendation treatment an increase of 29.46 % in soil organic carbon was observed for this treatment. The least organic carbon content value was recorded by the treatment without biochar application (T_1). The tender coconut husk biochar used for this study had high total carbon content of 70.1 %. This might be the reason for the increase in soil organic carbon consequent to biochar application. Van Zwieten *et al.* (2010) while assessing the application of biochar @ 10 t ha^{-1} in a ferrosol observed a significant increase in the total soil carbon to around 0.50 per cent.

Masto *et al.* (2013) found that the application of biochar @ 2 and 4 t ha^{-1} significantly increased the soil organic C from 0.81 per cent in control to 1.17 and 1.00 per cent at biochar and biochar + lignite fly ash treatment, respectively.

5.2.1.2.5 Available Nitrogen

Being one of the most important nutrient elements in plant nutrition, the behaviour and dynamics of soil nitrogen as influenced by biochar application needs special attention. A perusal of the data revealed that by the application of biochar treatments, there was an increase in the availability of N in soil at 6 MAP, followed by a decrease due to uptake of N by the plant at final harvest stage (Fig.11). Split dose application of N, K and Mg fertilizers at monthly intervals up to 6 MAP ensured steady and enhanced availability of these nutrients in soil.

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). The lowest available N content in the biochar alone treatment, invariably at all the three stages of analysis in the present study, is a clear manifestation of this fact.

To counter the potentially unavailable biochar N, Steiner (2007) found that there was a positive effect when biochar was applied in conjunction with inorganic fertilizer N, showing that biochar has the potential to improve the efficiency of added N fertilizers. Owing to the high CEC of biochar it is capable of efficiently adsorbing ammonia (NH_4^+) (Pandian *et al.*, 2016) and acts as a binder for ammonia in soil. Hence it has the potential to decrease ammonia volatilization from soil surfaces. Application of biochar @ 10 kg plant^{-1} along with STBR at the 3 MAP stage and application of biochar @ 10 kg plant^{-1} along with 75 % STBR at 6 MAP and at harvest stages recorded highest available N content in soil. The increased N availability in these two treatments is an explicit evidence of the positive counter effect brought about by the conjunctive use of biochar along with inorganic fertiliser N, on soil test basis. Higher nutrient retention capacity of biochar retained more nitrate nitrogen leading to an improvement in the nutrient supply to plants and reduced nutrient losses from soil by leaching and preventing ground water contamination (Chan and Xu 2009; Elangovan and Chandrasekaran, 2014). Biochar could adsorb ammonium ion predominantly by cation exchange and can be used as a nitrification inhibitor. Biochar, thus has a supplementary role as a slow release N fertilizer, in addition to its conjunctive effectiveness and efficiency.

5.2.1.2.6 Available Phosphorus

Available P status increased in all treatments at 3 MAP and 6 MAP stages which however decreased at final harvest stage, due to P uptake by the plant (Fig. 12). However available P was more in biochar + NPK as POP treatments when compared to biochar + STBR treatments. For the STBR treatments because of high initial available P, soil application of P was skipped. A comparison between the different quantities of biochar application along with nutrients revealed that 10 kg application resulted in higher availability of P. At 6 MAP and harvest stages biochar @ 10 kg plant^{-1} + NPK as per POP registered significantly highest value of 138.17 kg ha^{-1} and 117.65 kg ha^{-1} respectively. The observed increase in available phosphorus could be due to the presence of high phosphorous in the applied biochar. The increase in soil pH, that reduce the activity of Fe and Al, could also contribute for the highest values of available phosphorous in soils treated with biochar (Chintala *et al.,* 2014; DeLuca *et al.,* 2009).

Turner *et al.* (2006) reported that 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 and thereby create a sink on the availability of inorganic P for plants. Prabha *et al.* (2013) reported that the application of biochar @ 35 g pot^{-1} increases 63 % of available P content in soil. Masto *et al.* (2013) conducted a field experiment in an acidic red soil to study the effect of application of biochar on soil P availability and observed that an application of biochar @ 2 and 4 t ha^{-1} increased soil P availability by 110 per cent. Biochar thus induced changes in soil properties that could be beneficial for P retention in AEC sites and thereby aid in reducing P losses from agricultural fields (Soinne *et al.,* 2014).

5.2.1.2.7 Available Potassium

The details relating to the changes in available K due to the effect of various treatments are presented in Fig. 13. With the additions of biochar treatments, there was increase in the availability of K in soil at 6 MAP stage, followed by a decrease due to uptake of K by the plant at final harvest stage. There was no significant difference between the treatments in availability of K at 3 MAP. At 6 MAP and harvesting stages application of biochar @ 10 kg plant^{-1} along 75 % STBR registered an available K values of 288.13 kg ha^{-1} and 228.40 kg ha^{-1} respectively. Application of biochar in the rate of 10 kg resulted in more available K in soil. 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.

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 K availability by 64 %. Widowatil and Asnah (2014) suggested that application of biochar @ 30 t ha^{-1} could replace and reduce KCl fertilizer and increased the soil K availability from 69 to 89 %. Coumaravel *et al.* (2015) observed that on an average, an increase of 18.1, 14.3 and 4.3 per cent of available K was recorded for biochar with IPNS, biochar with NPK alone and biochar alone treatments over the initial status.

5.2.1.2.8 Available Calcium

It had been observed that application of biochar based treatments had significant influence on available Ca in soil at three crop growth stages. It is evident from the data that by the application of treatments, there was increase in the availability of Ca in soil at 6 MAP, followed by a decrease due to uptake of Ca by the plant at final harvest stage (Fig. 14). It was observed that biochar @ 10 kg plant^{-1} + NPK as per POP (T_3) treatment attained significantly highest available Ca at the 3, 6 MAP and at final harvest stages recording values of 447.50 mg kg^{-1}, 451.45 mg kg^{-1} and 434. 66 mg kg^{-1} respectively. 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 addition of lime in POP treatments above this 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.

Van Zwieten *et al.* (2010) reported that the application of biochar @ 10 t ha^{-1} in a ferrosol significantly increased exchangeable Ca levels from 1.23 cmol (+) kg^{-1} to 8.87 cmol (+) kg^{-1}. Major *et al.* (2010a) studied the effect of biochar @ 20 t ha^{-1} on Colombian savanna Oxisol, where a significant increase in availability of Ca from 77 to 320 per cent in maize.

5.2.1.2.9 Available Magnesium

It is evident from the data that by the biochar application, there was increase in the availability of Mg in soil at 6 MAP stage, followed by a decrease due to uptake of Mg by the plant at final harvest stage (Fig.15). There was no significant difference between the treatments on the availability of Mg at 3 MAP. At 6 MAP and harvest stages highest availability of Mg was recorded in biochar @ 10 kg plant^{-1} + 75 % as per STBR (T_{10}), the values recorded being 88.75 mg kg^{-1} and 72.56 mg kg^{-1} respectively. At the final harvest stage, it was observed that the Mg content increased by 57.46 % as compared to the POP treatment, due to the addition from biochar and

136

$MgSO_4$ fertilizer. In all growth stages biochar along with STBR treatments recorded higher available Mg in soil. Sukartono *et al.* (2011) concluded that application of coconut shell biochar increased the soil Mg status from 1.32 to 1.54 cmol kg^{-1}. Major *et al.* (2010a) also found that available Mg content increased from 64 to 217 % when wood biochar was applied @ 20 t ha^{-1} in maize.

5.2.1.2.10 Available Sulphur

It is evident from the data that by the application of treatments, there was increase in the availability of S in soil at 6 MAP, followed by a decrease due to uptake of S by the plant at final harvest stage (Fig. 16). Application of biochar 10 kg $plant^{-1}$ + 75% STBR (T_{10}) recorded highest available S in soil with values of 33 mg kg^{-1} and 34.46 mg kg^{-1} at 3 MAP and harvest stages respectively. At 6 MAP stage, biochar @ 10 kg $plant^{-1}$ + (NPK + secondary and micronutrients as per STBR) recorded highest available S in soil compared to all other treatments. The S status of the soil at final harvest stage increased to the tune of 53.7 % as compared to package of practices recommendation. The observed increase in available S status is due to the addition from biochar and $MgSO_4$ fertilizer.

5.2.1.2.11 Available Zinc and Copper

Analysis of the data revealed that application of biochar had significant influence on available Zn and Cu in soil at different stages of crop growth (Fig. 17 and 18). It is evident from the data that by the application of treatments, there was increase in the availability of Zn and Cu in soil at 6 MAP, followed by a decrease due to uptake of Zn and Cu by the plant at final harvest stage. Application of biochar 10 kg $plant^{-1}$ along with 75 % STBR recorded the highest Zn and Cu at three crop growth stages. This is due to the fact that biochar from tender coconut husk is a rich source of micronutrients. Zn and Cu are associated with many organic compounds in biomass and largely retained during biochar formation (Amonette and Joseph, 2009).

137

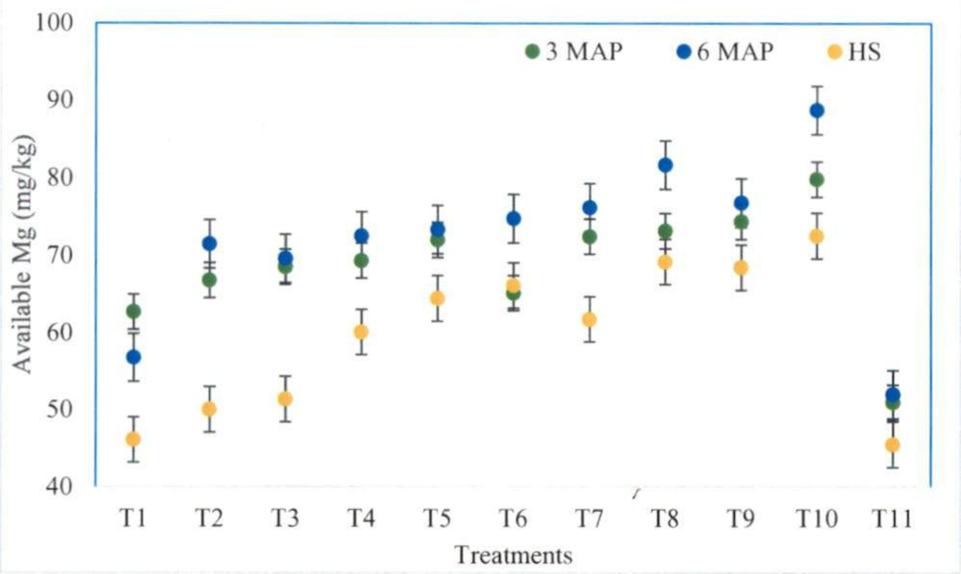


Fig. 15. Effect of treatments on soil available Mg at different stages

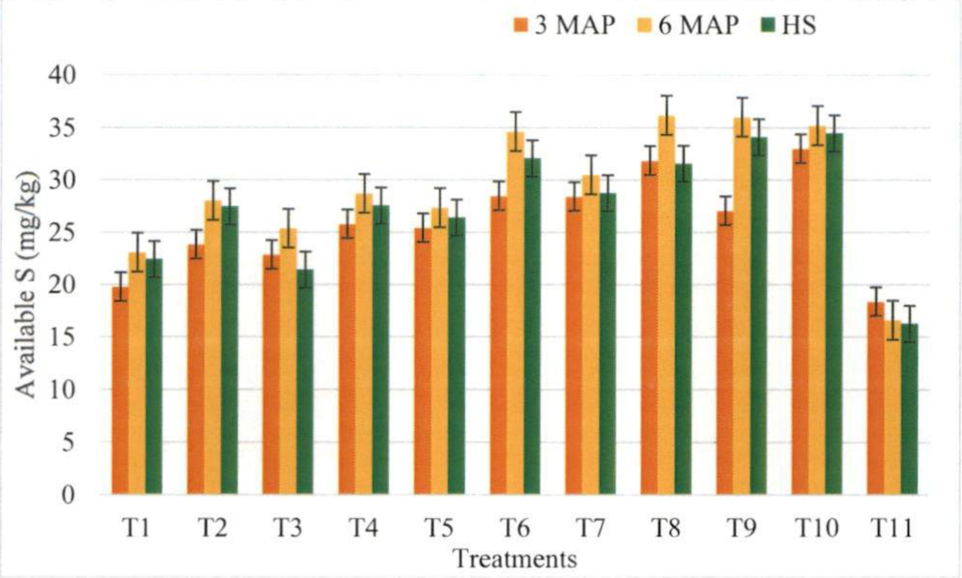


Fig. 16. Effect of treatments on soil available S at different stages

138

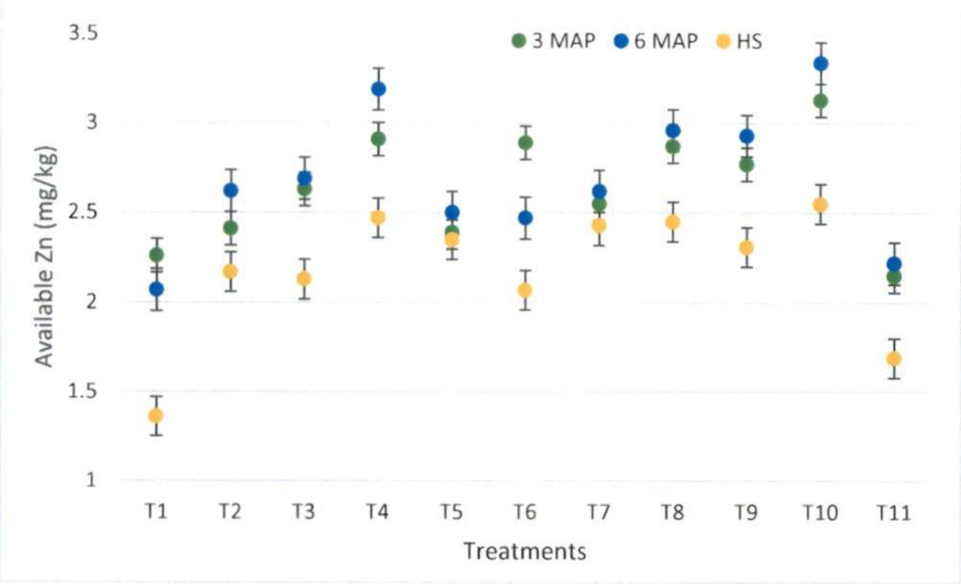


Fig. 17. Effect of treatments on soil available Zn at different stages

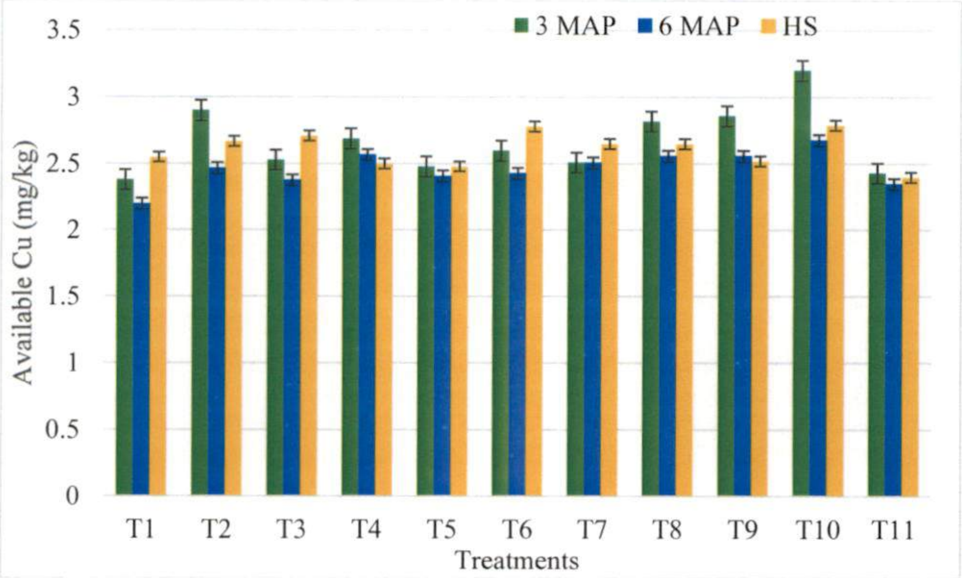


Fig. 18. Effect of treatments on soil available Cu at different stages

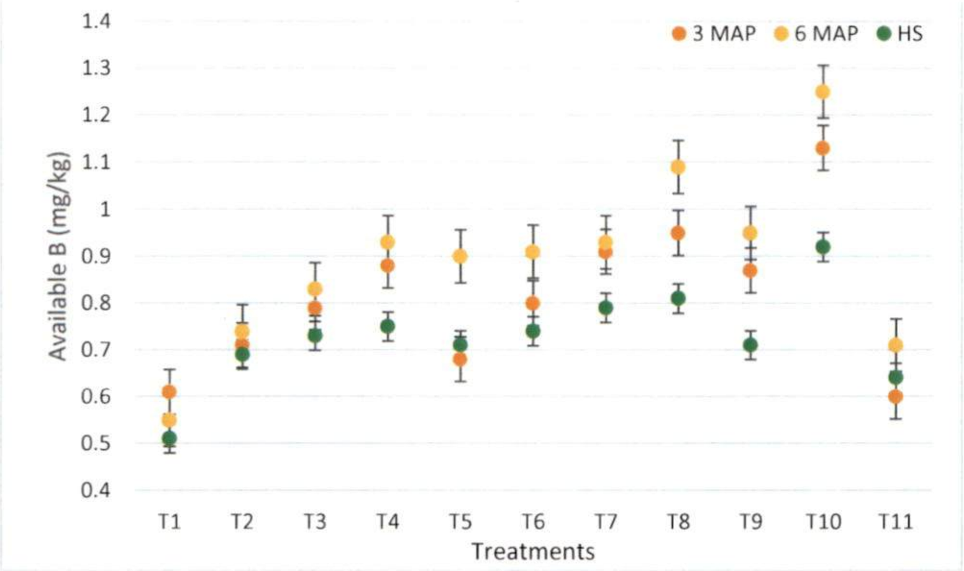


Fig. 19. Effect of treatments on soil available B at different stages

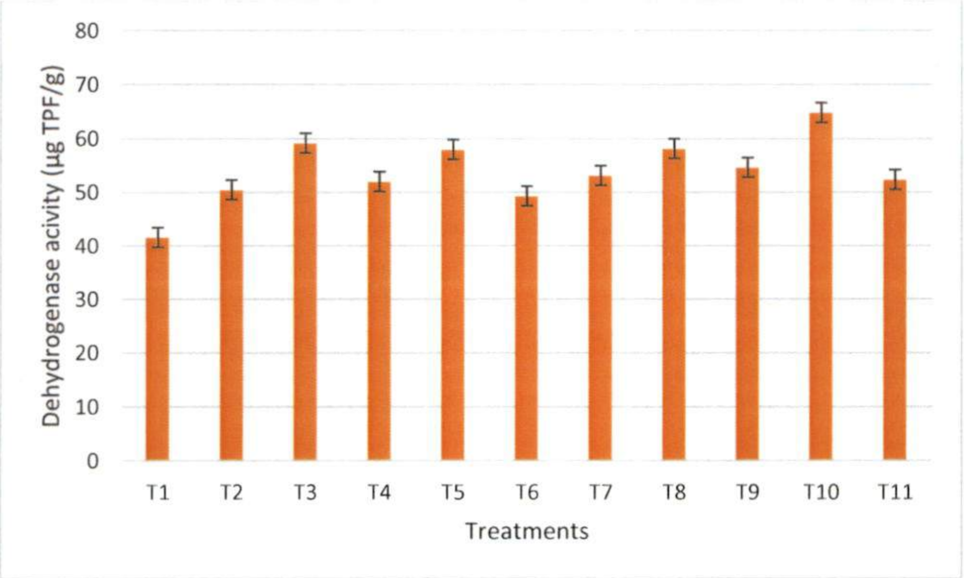


Fig. 20. Effect of treatments on soil dehydrogenase activity at harvest stage

5.2.1.2.12 Available Boron

Available B content of the soil was influenced by biochar based treatments. There was an increase in the availability of B in soil at 6 MAP stage, followed by a decrease due to uptake of B by the plant at final harvest stage (Fig. 19). There was no significant difference between the treatments in availability of B at 3 MAP. Application of 10 kg biochar along with 75% STBR (T_{10}) recorded the highest values of 1.25 mg kg^{-1} and 0.92 mg kg^{-1}, at 6 MAP and final harvest stages respectively. The improvement in B status is attributed to the relatively high B content in the biochar made from tender coconut husk and also due to the fact that biochar can sorb considerable amount of H_3BO_3 on its surface because of its high AEC and this resulted in reduced leaching of this nutrient. Higher application biochar resulted in higher available B in soil.

5.2.1.2.13 Dehydrogenase Activity

The effect of biochar based treatments on the dehydrogenase activity of the soil at final harvest stage was significant. The highest dehydrogenase activity in soil was obtained in biochar @ 10 kg plant^{-1} + 75% STBR (T_{10}) (64.87 µg TPF g^{-1} 24 h^{-1}) which was on par with BC @ 10 kg plant^{-1} + NPK as per POP (T_3) (59.18 µg TPF g^{-1} 24 h^{-1}) and biochar @ 10 kg plant^{-1} + STBR (T_8) (58.19 µg TPF g^{-1}) (Fig. 20). Higher application of biochar resulted in higher biological activity in soil. Biochar being highly porous material and the pores with nutrients and water provide the most conducive condition for the proliferation of micro-organism. The large internal surface area of biochar expands the organic and inorganic compound adsorption capability of soil, such that the supply of mineral nutrients and energy to microbes is increased (Gul *et al.*, 2015). Masto *et al.* (2013) reported that the application of biochar @ 2 and 4 t ha^{-1} increased soil enzymes of dehydrogenase activity (60.70 per cent) and microbial biomass (25.3 per cent).

5.2.3 Foliar Nutrient Concentration of Nendran Banana as Influenced by biochar Application

5.2.3.1 Foliar Nitrogen

The highest foliar N concentration was recorded with the application of biochar @ 10 kg plant^{-1} along 75% STBR which was on par with biochar 5 kg plant^{-1} + 75% NPK as per POP at final harvest stage. The N availability in soil was also superior for the same treatment. Chan *et al.* (2007) found that additions of biochar plus fertilizer (NH^{4+}) increased yields more than the addition of fertilizer alone, indicating reduced N leaching and increased N use efficiency. Furthermore, Chan *et al.* (2007) observed an increase in the uptake of N at higher levels of biochar.

5.2.3.2 Foliar Phosphorus

The index leaf tissue analysis revealed significant difference in the foliar P concentration among the treatments at harvest stage. The highest P concentration level was registered with biochar @ 5 kg plant^{-1} + 75% NPK as per POP (T_4). The higher foliar P concentration is due to the contribution from biochar as well as P fertilizer application. Higher levels of biochar application will results in higher availability of P in soil which in turn will lead to higher uptake. Chan *et al.* (2007) conducted studies on the response of dry matter production of radish using green wastes and found that the biochar application increased the P concentration.

5.2.3.3 Foliar Potassium

The foliar K concentration of different treatments exhibited significant variation at harvest stage. Highest K concentration of 2.24 % was recorded with the application of biochar 10 kg plant^{-1} + 75% (NPK + secondary and micronutrients as per STBR) (T_{10}). This might be due to the high K content (2.26 %) of biochar. This in turn amplified the foliar K concentration.

5.2.3.4 Foliar Calcium

Application of biochar @ 10 kg plant^{-1} + NPK as per POP (T_3) significantly increased calcium concentration (3.33 %) as compared to all other treatments at harvest stage. The high foliar Ca concentration is attributed to the relatively high 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. 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 tasselling stage, by the application of biochar @ 20 t ha^{-1}.

5.2.3.5 Foliar Magnesium

Effect of various treatments at harvest stage was significant on the foliar Mg concentration. However the foliar Mg concentration ranged between 0.14 % and 0.08 % in the various treatments. The highest Mg concentration of 0.14 % was found in the biochar @ 10 kg plant^{-1} + 75 % STBR (T_{10}). This is due to STBR application and contribution from biochar.) Similar observations about enhancement in Mg content in maize leaf from 0.92 to 1.03 g kg dry matter^{-1} when biochar was applied @ 20 t ha^{-1} was reported by Major *et al.* (2010a).

5.2.3.6 Foliar Sulphur

The highest concentration of 0.21 % foliar S was found in the biochar @10 kg along 75 % (NPK + secondary and micronutrients as per STBR) (T_{10}) treatment at harvest stage. The higher content of S in soil is due to application of biochar along with $MgSO_4$ which improved the uptake of S by the banana plant.

5.2.3.7 Foliar Iron, Manganese, Zinc, Copper and Boron

It had been observed that the treatments had significant influence on foliar Fe, Mn and Zn concentration at final harvest stage. The highest foliar concentration of Fe, Mn and Zn were noticed in biochar @ 10 kg plant^{-1} + 75 % (NPK + secondary and micronutrients as per STBR) (T_{10}) with values of 877.83 mg kg^{-1}, 1053 mg kg^{-1} and 16.58 mg kg^{-1} respectively. The analytical results of foliar Cu and B concentration with respect to various treatments showed that there was no significant difference between the treatments. The high foliar concentration in the biochar treated plants is attributed to the increased availability of the Fe, Mn and Zn nutrients in soil that resulted in better utilization, improved uptake by the crop and efficient partitioning to foliar parts.

5.2.4 Effect of Biochar on Nutrient Use Efficiency

The highest nutrient use efficiency of 50.40 % was recorded in the 10 kg biochar applied along with 75 % STBR (T_{10}). Biochar from tender coconut husk has high surface area, CEC and AEC which will help in the adsorption of nutrients and it is released for the plant uptake slowly without much loss. Chan and Xu (2009) reported that improved nutrient use efficiency, referring to crops giving rise to higher yield per unit of fertilizer applied was thus shown as a major positive attribute of the biochar application.

5.2.5 Growth Characters, Yield and Fruit Quality of Banana as Influenced by Biochar Based Treatments

Plant biometric characters like plant height at 2, 4, 6 and 8 MAP, number of leaves per plant at 2 and 6 MAP and pseudostem girth at 4 and 8 MAP were highest in the biochar @ 10 kg plant^{-1} + 75% (NPK + secondary and micronutrients as per of STBR (T_{10}) treatment followed by 5 kg biochar + 75% of NPK as per POP. Biochar applications to soils may increase plant growth and crop yields. Biochar has been reported to have both direct and indirect influence on soil nutrient availability, which can have impacts on plant growth (Blackwell *et al*., 2009).

The total dry matter production (12742.15 kg ha^{-1}) was significantly higher with biochar (10 kg plant^{-1}) with 75% of STBR followed by 5 kg biochar+ 75% NPK as per POP. It is quite evident from Table 16 that the treatment which received biochar alone @10 kg without any inorganic fertilisers realised the lowest yield and yield attributes. Despite the fact that biochar is a store house of several nutrients required for plant growth, the quantity of nutrients are not at all sufficient to meet the crop requirement. Addition of nutrients are necessary for good crop growth and yield. Biochar @ 10 kg plant^{-1} added with 75 % of STBR fertilizer nutrients resulted in the highest bunch weight (9.34 kg plant^{-1}), number of hands per bunch (5.25), number of fingers per bunch (46.16) and both length (22.83 cm) and girth (12.73 cm) of the index finger, followed by biochar (5 kg plant^{-1}) with 75% NPK as per POP. This implies that the readily available essential nutrients in the inorganic fertilisers applied in conjunction with biochar was capable of supplying the required nutrients for crop growth and production. Fruit quality parameters like TSS (34 ^{0} B), ascorbic acid content (2.18 mg 100g^{-1}) and shelf life (9.66) of fruits were found to be superior in the treatment 10 kg biochar + 75% STBR application. The highest B:C ratio of 2.38 was recorded by the 10 kg biochar applied treatment along with 75% STBR application. There was progressive improvement in the physical, chemical and biological properties of soil to a great extent which resulted in better growth, profitable yield and superior fruit quality of banana.

5.2.6 Biochar Based Nutrient Mix for Nendran Banana

Based on the best treatment (T_{10}) biochar based nutrient mix was prepared by mixing 10 kg biochar + urea $_{260.21g}$ + MOP $_{528.75g}$ + $MgSO_4$ $_{23.44g}$ for Loamy, Kaolinitic, Isohyperthermic, Typic Kandiustults of Vellayani series. Application of P was skipped because the soil recorded very high available P. Secondary as well as micronutrients were in the sufficient range except Mg. The nutrient mix had stable properties and cost of nutrient mix was Rs. 110 per plant. For other soils also biochar based nutrient mix can be prepared based on the soil test values. Based on the second best treatment it is possible to give a blanket recommendation for nendran banana by mixing 5 kg biochar + urea $_{142.50g}$ + rock phosphate $_{86.25g}$ + MOP $_{337.50g}$ and the cost was calculated as Rs. 80 per plant.

Conversion of tender coconut husk biomass to biochar by using refined technology is a cost effective and efficient way for waste management. Biochar is a rich source of carbon and all the essential plant nutrients, a potential tool for carbon sequestration and finally best soil amendment which can improve physical, chemical and biological properties of soil to a great extent and crop productivity.

Table 40. Comparison between control and the best treatment

Parameters	Control (T_1- POP)	Best treatment (T_{10}- BC 10 kg plant^{-1} + 75% (NPK as per STBR)	Units increase or decrease	Percentage increase or decrease
Liming effect (pH)	4.57	5.17	0.60	13.12
CEC	2.59	5.18	2.59	100
WHC (%)	24.30	38.18	13.88	57.11
Bulk density	1.32	1.23	0.09 (decrease)	7.31 (decrease)
Porosity (%)	43.12	58.35	15.23	35.32
Organic C (%)	1.12	1.45	0.33	29.46
Yield (kg plant^{-1})	6.21	9.34	3.13	50.40

SUMMARY

6. SUMMARY

A study entitled 'Technology refinement for biochar production and evaluation of its effect on soil health and crop productivity' was undertaken at the College of Agriculture, Vellayani from March 2015 to June 2016. The objective of the investigation was refinement of technology for micro level biochar production from tender coconut husk and evaluation of its effect on soil health, yield and quality of banana (*Musa* spp.). A summary of the salient results of the study are presented.

6.1. REFINEMENT OF BIOCHAR PRODUCTION TECHNOLOGY

- An indigenously designed and fabricated micro biochar kiln for the pyrolytic conversion of tender coconut husk to biochar was developed.
- The micro biochar kiln consists of a temperature monitoring enabled, double barrel reactor unit with chimney and a cooling assembly for condensation and collection of syngas.
- Reactor unit of 30 kg biomass capacity and recovery percentage of 50 % was obtained, which was 17 % more than the biochar kiln designed earlier.

6.2. BIOCHAR CHARACTERIZATION

- Chemical parameters revealed that the biochar had an alkaline pH (8.53), high total organic carbon (70.10 %), CEC (15.26 cmol kg^{-1}) and AEC (5.64 cmol kg^{-1}).
- Nutrient composition of the biochar produced by the refined technology is N (1.52 %), P (0.40 %), K (2.26 %), Ca (0.54 %), Mg (0.46 %), S (0.27 %), Fe (89.9 mg kg^{-1}), Mn (2.84 mg kg^{-1}) and B (6.78 mg kg^{-1}).
- The heavy metal contents (Pb, Cd, Ni, Cr, Zn and Cu) were found at minimum levels compared to the threshold levels.
- C:N, C:P, C:S and C:N:P:S ratios were 46.11, 175.25, 259.62 and 350:7.5:2:1 respectively.

6.3. SYNGAS ANALYSIS

- The syngas produced during pyrolysis was analyzed by gas chromatography and it was composed of carbon dioxide (67.70 %), methane (22.89 %), oxygen (8.74 %), hydrogen (0.66 %) and n-Butane (0.001 %) respectively on normal mol % (dry) basis. Carbon monoxide and nitrogen were absent.
- Since recovery percentage was more, the quantity of syngas produced was very less when compared to the previous biochar production unit and the composition of syngas produced revealed that it can't be used as a bioenergy source.
- There was no production of bio oil during pyrolysis.
- All these qualities attribute this refined technology as the most effective in carbon sequestration and safe waste management.

6.4. FIELD EXPERIMENT FOR EVALUATION OF BIOCHAR ON SOIL HEALTH, YIELD AND QUALITY OF BANANA

- Plant biometric characters like plant height at 2, 4, 6 and 8 MAP, number of leaves per plant at 2 and 6 MAP and pseudostem girth at 4 and 8 MAP were highest in the T_{10} (Biochar @ 10 kg plant^{-1} + 75 % (NPK + secondary & micronutrients as per STBR)) treatment followed by 5 kg biochar + 75 % of NPK as per POP.
- The total dry matter production was significantly higher with biochar (10 kg plant^{-1}) with 75% of STBR followed by 5 kg biochar+ 75 % NPK as per POP.
- Biochar @ 10 kg plant^{-1} coupled with 75 % of STBR resulted in the highest bunch weight, number of hands per bunch, number of fingers per bunch and both length and girth of the index finger, followed by biochar (5 kg plant^{-1}) with 75 % NPK as per POP.
- 10 kg biochar along with 75 % STBR enhanced the physical properties of the soil by imparting 57.11 % increase in the WHC, 35.32 % increase in porosity and a 7.31% decrease in the bulk density than application with the treatment corresponding with FYM + NPK as per POP.

- A significant decrease in soil acidity was observed in the biochar based treatments as compared to the FYM applied treatments with a 0.6 units increase in pH in the T_{10} treatment.
- The highest OC content of 1.45 % and a 100 % increase in CEC of the soil resulted when 10 kg biochar along with 75 % of STBR were applied instead of FYM based POP recommendation.
- The 10 kg biochar treatment with 75 % of STBR significantly increased the soil available N, K, Mg and B at the active growth and harvest stages of banana. Zn content was highest in this treatment throughout all stages.
- The superiority of the biochar based treatments as compared to FYM based treatments in promoting the growth and development of soil microorganisms in the rhizosphere was evident with a 55.9 % enhancement in soil dehydrogenase activity in the T_{10} treatment than in the FYM based POP treatment.
- Biochar @ 10 kg per plant applied with 75 % STBR recorded highest foliar N, K, Mg, S and micronutrients Fe, Mn, Zn concentration.
- The highest nutrient use efficiency of 50.4 % was also recorded in the 10 kg biochar applied plots along with 75 % STBR.
- Fruit quality parameters like TSS, ascorbic acid content and shelf life of fruits were found to be superior in the T_{10} treatment.
- The highest B:C ratio of 2.38 was recorded by the 10 kg biochar applied treatment along with 75 % STBR application.
- Based on this a biochar based nutrient mix was prepared by mixing 10 kg biochar with urea $_{260.21g}$, MOP $_{528.75g}$ and $MgSO_4$ $_{23.44g}$ for Typic Kandiustults of Vellayani series.
- A comparison of the different levels of biochar application revealed that more the application of biochar, higher will be the improvement in physical, chemical and biological properties of the soil and in turn on soil health.

It is concluded that a prototype of micro biochar kiln was indigenously designed and fabricated for the pyrolytic conversion of tender coconut husk biomass to biochar with cooling assembly for syngas collection. Biochar produced had ideal physical and chemical properties that qualify it to be used as a soil amendment, environmentally safe contributing to the soil carbon pool. Biochar based fertilizers in general, and biochar (10 kg plant^{-1}) along with 75 % soil test based recommendation in particular, enhanced the soil physical properties, decreased soil acidity, promoted rhizospheric microorganisms, increased the soil fertility status enabling efficient nutrient use and resulted in higher growth, profitable yield and superior fruit quality of banana.

FUTURE LINE OF WORK

Conversion of biowaste to biochar by the process of pyrolysis is the most intelligent way of recycling organic waste and thus reducing environmental pollution.

- Impact of biochar application on different crops and cropping system.
- Enrichment of biochar at higher application rates with nutrients (organic or inorganic) and its application in soil will be an efficient approach for recycling of nutrients.
- Study of biochar as a potential tool to reduce GHG emissions from soil, more research is required to understand the mechanisms which underlie these processes.
- The sorption-desorption study with all nutrients in order to find out the adsorption and release pattern.
- Biochar utilization for bioremediating heavy metals and organic pollutants in 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.
- Further research is necessary on application of biochar as a soil amendment in acid soils of Kerala.

- Quantify the carbon sequestration potential of biochars produced from different bio-wastes to biochar and its role in mitigating climate change.
- Temporal variation in CEC of soil due to biochar application in different soil types.
- Study of nutrient dynamics under biochar application in various soils.

REFERENCES

7. REFERENCES

Adam, J. C. 2009. Improved and more environmentally friendly charcoal production system using a low-cost retorte kiln (Eco-charcoal), Renew. *Energy* 34 (8): 1923-1925.

Agbna, G.H., Dongli, S., Zhipeng, L., Elshaikh, N.A., Guangcheng, S., and Timm, L.C. 2017. Effects of deficit irrigation and biochar addition on the growth, yield, and quality of tomato. *Scientia Hortic.* 222: 90-101.

Agegnehu, G., Srivastava, A.K., and Bird, M.I. 2017. The role of biochar and biochar-compost in improving soil quality and crop performance: A review. *Appl. Soil Ecol.* 119: 156-170.

Agrafiotia, E., Bourasa, G., Kalderisb, D., and Diamadopoulos, E. 2013. Biochar production by sewage sludge pyrolysis. *J. Anal. Appl. Pyrol.* 101: 72-78.

Akhtar, S. S., Li, G., Andersen, M. N., and Liu, F. 2014. Biochar enhances yield and quality of tomato under reduced irrigation. *Agric. Water Manage.* 138: 37-44.

Amonette, J. and Joseph, S. 2009. Characteristics of Biochar - Micro-Chemical Properties, In: Lehmann, J. and Joseph, S. (eds.). *Biochar for Environmental Management: Science and Technology*, Earthscan, London, UK, 33p.

Angın, D. 2013. Effect of pyrolysis temperature and heating rate on biochar obtained from pyrolysis of safflower seed press cake. *Bioresour. Technol.* 128: 593-7.

Asai, H., Samson, B.K., Stephan, H.M., Songyikhangsuthor, K., Homma, K., Kiyono, Y., Inoue, Y., Shiraiwa, T., and Horie, T. 2009. Biochar amendment techniques for upland rice production in northern Laos. *Field Crops Res.* 111: 81-84.

Atkinson, C.J. Fitzgerald, J.D., and Hipps, N.A. 2010. Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: A review. *Plant Soil.* 337: 1-18.

Azeem, M., Hayat, R., Hussain, Q., Ahmed, M., Imran, M., and Crowley, D.E. 2016. Effect of biochar amendment on soil microbial biomass, abundance and enzyme activity in the mash bean field. *J. Biodiversity Environ. Sci.* 8(6): 1-13.

Bass, A.M., Bird, M.I., Kay, G., and Muirhead, B. 2016. Soil properties, greenhouse gas emissions and crop yield under compost, biochar and co-composted biochar in two tropical agronomic systems. *Sci. Total Environ.* 550: 459-470.

Belyaeva, O.N. and Haynes, R.J. 2012. Comparison of the effects of conventional organic amendments and biochar on the chemical, physical and microbial properties of coal fly ash as a plant growth medium. *Environ. Earth Sci.* 66(7): 1987-1997

Bera, T., Collins, H.P., Alva, A.K., Purakayastha, T.J., and Patra, A.K. 2016. Biochar and manure effluent effects on soil biochemical properties under corn production. *Appl. Soil Ecol.* 107: 360-367.

Bingham, F.T. 1982. Boron. In: Page, A.L. (ed.), *Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties, Agronomy Monograph 9.2.* American Society of Agronomy, Soil Science Society of America, Madison, WI, pp. 431-447.

Blackwell, P., Riethmuller, G., and Collins, M. 2009. Biochar Application to Soil (Chapter 12), In: Lehmann, J. and Joseph, S. (eds.). *Biochar for*

Environmental Management: Science and Technology, Earthscan, London, UK, 207p.

Boukis, I. 1997. *Fast pyrolysis of biomass in a circulating fluidized bed reactor*. Ph.D. thesis, Birmingham, UK: University of Aston, 199p.

Brown, R. A., Kercher, A. K., Nguyen, T. H., Nagle, D. C., and Ball, W. P. 2006. Production and characterization of synthetic wood chars for use as surrogates for natural sorbents. *Org. Geochem.* 37: 321-333.

Bunzl, K. and Sansoni, B. 1976. Determination of the ion exchange capacity of solid ion exchangers by difference weighting. *Analyt. Chem.* 48(14): 2279-2280.

Cao, X. and Harris, W. 2010. Properties of dairy-manure-derived biochar pertinent to its potential use in remediation. *Bioresource Technol.* 101: 5222-5228.

Castellini, M., Giglio, L., Niedda, M., Palumbo, A. D., and Ventrella, D. 2015. Impact of biochar addition on the physical and hydraulic properties of a clay soil. *Soil Till. Res.* 154: 1-13.

Chan, K. Y. and Xu, Z. H. 2009. Biochar - Nutrient properties and their enhancement (Chapter 5), In: Lehmann, J. and Joseph, S. (eds.), *Biochar for Environmental Management: Science and Technology*, Earthscan, London, UK. 67p.

Chan, K. Y., Van Zwieten, L., Meszaros, I., Downie, A., and Joseph, S. 2007. Agronomic values of greenwaste biochar as a soil amendment. *Aus. J. Soil Res.* 45: 629-634.

Chen, X., Chen, G., Chen, L., Chen, Y., Lehmann, J., McBride, M.B., and Hay, A.G. 2011. Adsorption of copper and zinc by biochars produced from pyrolysis of hardwood and corn straw in aqueous solution. *Bioresource Technol.* 102(19): 8877-8884.

Cheng, C. H., Lehmann, J., Thies, J., Burton, S. D., and Engelhard, M. H. 2006. Oxidation of black carbon by biotic and abiotic processes. *Org. Geochem*. 37: 1477-1488.

Cheng, G., Li, Q., Qi, F., Xiao, B., Liu, S., Hu, Z., and He, P. 2012. Allothermal Gasification of Biomass Using Micron Size Biomass as External Heat Source. *Bioresource Technol.* 107: 471-475.

Chesnin, L. and Yien, C. H. 1950. Turbidimetric determination of available sulphates. *Soil Sci. Soc. Am. Proc*. 15: 149-151.

Chintala, R., Mollinedo, J., Schumacher, T.E., Malo, D.D., and Julson, J.L. 2014. Effect of biochar on chemical properties of acidic soil. *Archives Agron. Soil Sci.* 60(3): 393-404.

Cornelissen, G., Pandit, N.R., Taylor, P., Pandit, B.H., Sparrevik, M., and Schmidt, H.P. 2016. Emissions, Char Quality, of flame-curtain" Kon Tiki" kilns for farmer-scale charcoal/biochar production. *PLoS One* 11 (5): e0154617.

Coumaravel, K., Santhi, R., and Maragatham, S. 2015. Effect of biochar on yield and nutrient uptake by hybrid maize and on soil fertility. *Indian J. Agric. Res.* 49 (2): 185-188.

Dainy, M.M.S. 2015. *Investigation on the efficacy of biochar from tender coconut husk for enhanced crop production*. Ph. D. thesis, Kerala Agricultural University, 208p.

DeLuca, T. H., MacKenzie, M. D., and Gundale, M. J. 2009. Biochar effects on soil nutrient transformations. In: Lehmann, J., Joseph, S. (eds.), *Biochar for Environmental Management: Science and Technology*. Earthscan, London. pp. 251-270.

Delwiche, K.B., Lehmann, J., and Walter, M.T. 2014. Atrazine leaching from biochar-amended soils. *Chemosphere* 95: 346-352.

Downie, A., Crosky, A., and Munroe, P. 2009. Physical properties of biochar. In: Lehmann, L., Joseph, S. (eds.), *Biochar for Environmental Management: Science and Technology*. Earthscan Publishers Ltd, London. pp. 13-32.

Dufour, A., Celzard, A., Fierro, V., Martin, E., Broust, F., and Zoulalian, A. 2008. Catalytic decomposition of methane over a wood char concurrently activated by a pyrolysis gas. *Appl. Catal.* 346: 164-173.

Duku, M.H., Gu, S., and Hagan, E.B. 2011. Biochar production potential in Ghanada review, Renew. *Sustain. Energy Rev.* 15(8): 3539-3551.

Elangovan, R. and Chandrasekaran, N. 2014. Effect of biochar application on soil properties and quality parameters in cotton. *Asian J. Soil Sci.* 9: 1-10.

Fisher, T., Hajalgol, M., Wayamack, B., and Kellogg, D. 2002. Pyrolysis behavior and kinetics of biomass derived material. *J. Anal. Appl. Pyrol.* 62: 331-349.

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D.W., Haywood, J., Lean, J., Lowe, D.C., and Myhre, G. 2007. Changes in atmospheric constituents and in radiative forcing. *Chapter 2, in Climate Change The Physical Science Basis.* pp. 131-217.

Fujita, I., Tomooka, J., and Sugimura, T. 1991. Sorption of anionic surfactants with wood charcoal. *Bull Chem. Soc. Jpn.* 64:738-740.

Garcia-Montiel, D. C., Neill, C., Melillo, J., Thomas, S., Steudler, P.A., and Cerri, C. C. 2000. Soil phosphorus transformations following forest clearing for pasture in the Brazilian Amazon. *Soil Sci. Soc. Am. J.* 64: 1792-1804

Gaskin, J. W., Speir, R. A., Harris, K., Das, K. C., Lee, R. D., Morris, L. A., and Fisher, D. S. 2010. Effect of peanut hull and pine chip biochar on soil nutrients, corn nutrient status and yield. *Agron. J.* 102: 623-633.

Geim, A. K. and Novoselov, K. S. 2007. The Rise of Graphene. *Nature Materials.* 6 (3): 183-191.

Githinji, L. 2014. Effect of biochar application rate on soil physical and hydraulic properties of a sandy loam. *Arch. Agron. Soil Sci*. 60 (4): 457-470.

Glaser, B., Haumaier, L., Guggenberger, G., and Zech, W. 2001. The Terra Preta phenomenon: A model for sustainable agriculture in the humid tropics. *Naturwissenschaften.* 88: 37-41.

Glaser, B., Lehmann, J., and Zech, W. 2002. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal- a review. *Biol. Fertil. Soils* 35: 219-230.

Gomez, K.A. and Gomez, A.A. 1984. *Statistical Procedures for Agricultural Research*. John Wiley and Sons, 639p.

Graber, E.R., Harel, Y.M., Kolton, M., Cytryn, E., Silber, A., David, D.R., Tsechansky, L., Borenshtein, M., and Elad, Y. 2010. Biochar impact on development and productivity of pepper and tomato grown in fertigated soilless media. *Pl. Soil.* 337: 481-496.

Greenberg, A.E., Clesceri L.S., and Eaton A.D. 1992. *Standard Methods for the Examination of Water and Wastewater*, 18th (Ed.). American Public Health Association, Washington, 75p.

Gul, S., Whalen, J. K., Thomas, B. W., and Sachdeva, V. 2015. Physico-chemical properties and microbial responses in biochar-amended soils: mechanisms and future directions. *Agric. Ecosyst. Environ.* 206: 46-49.

Gupta, R.P. and Dakshinamoorthi, C. 1980. *Procedures for Physical Analysis of Soil and Collection of Agro-Meteorological Dates.* India Meteorological Department, Pune. 74p.

Gupta, U.C. 1967. A simplified method for determining hot water soluble boron in podzol soils. *Soil Sci.* 103(6): 424-428.

Gwenzi, W., Chaukura, N., Mukome, F.N., Machado, S., and Nyamasoka, B. 2015. Biochar production and applications in sub-Saharan Africa: Opportunities, constraints, risks and uncertainties. *J. Environ. Manag.* 150: 250-261.

Haider, G., Koyro, H.W., Azam, F., Steffens, D., Müller, C., and Kammann, C. 2015. Biochar but not humic acid product amendment affected maize yields via improving plant-soil moisture relations. *Plant soil* 395(1-2): 141-157.

Hall, D. O. and Rosillo-Calle, F. 1998. *Biomass resources other than wood, World Energy Council, London*

Hall, D. O., Rosillo-Calle, F., and de Groot, P. 1992. Biomass energy: lessons from case studies in developing countries. *Energy Policy*. 20(1): 62-73.

Hamdani, S.A.F., Aon, M., Ali, L., Aslam, Z., Khalid, M., and Naveed, M. 2017. Application of dalbergia sissoo biochar enhanced wheat growth, yield and nutrient recovery under reduced fertilizer doses in calcareous soil. *Pakistan J. Agric. Sci.* 54(1): 107-115.

Hardie, M., Clothier, B., Bound, S., Oliver, G., and Close, D. 2014. Does biochar influence soil physical properties and soil water availability? *Plant Soil*. 376: 347-361.

He, Y.D., Zhai, Y.B., Li, C.T., Yang, F., Chen, L., Fan, X.P., Peng, W.F., and Fu, Z.M. 2010. The fate of Cu, Zn, Pb and Cd during the pyrolysis of sewage sludge at different temperatures. *Environ. Technol.* 35: 567-574.

Herath, I., Kumarathilaka, P., Navaratne, A., Rajakaruna, N., and Vithanage, M. 2015. Immobilization and phytotoxicity reduction of heavy metals in serpentine soil using biochar. *J. Soils Sediments* 15: 126-138.

Hesse, P.R. 1971. *A textbook of soil chemical analysis*. John Murray Ltd, London, 520p.

Hossain, M. K., Strezov, V., and Nelson, P. F. 2015. Comparative assessment of the effect of wastewater sludge biochar on growth, yield and metal bioaccumulation of cherry tomato. *Pedosphere* 25: 680-685.

Huang, M., Yang, M., Qin, H., Jiang, L., and Zou, Y. 2013. Quantifying the effect of biochar amendment on soil quality and crop productivity in Chinese rice paddies. *Field Crops Res*. 154: 172-177.

Hussain, M., Farooq, M., Nawaz, A., Al-Sadi, A. M., Solaiman, Z. M., Alghamdi, S. S., Ammara, U., Yong, S. O., and Siddique, K. H. M. 2017. Biochar for crop production: potential benefits and risks, *J. Soil. Sediment* 17: 685-716.

IBI (International Biochar Initiative) 2014. Standardized Product Definition and Product Testing Guidelines for Biochar That Is Used in Soil, IBI-STD-2.0, IBI Biochar Standards. www.biochar-international/org.characterizationstandard, Accessed July 15, 2016, 60p.

Ippolito, J. A., Novak, J. M., Busscher, W. J., Ahmedna, M., Rehrah, D., and Watts, D.W. 2012. Switchgrass biochar affects two aridisols. *J. Environ. Qual.* 41: 1123-1130.

Jackson, M. L. 1973. *Soil Chemical Analysis* (2nd Ed.). Prentice Hall of India, New Delhi, 498p.

Jeffery, S., Verheijen, F.G.A., van der Velde, M., and Bastos, A.C. 2011. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agric. Ecosyst. Environ.* 144: 175-187.

Jetter, J., Zhao, Y., Smith, K. R., Khan, B., Yelverton, T., DeCarlo, P., and Hays, M. D. 2012. Pollutant emissions and energy efficiency under controlled conditions for household biomass cookstoves and implications for metrics useful in setting international test standards. *Environ. Sci. Technol.* 46(19): 10827-10834.

Jha, P., Biswas, A.K., Lakaria, B.L., and Rao, A.S. 2010. Biochar in agriculture–prospects and related implications. *Current sci.* 99(9): 1218-1225.

Jin, H., Arazo, R.O., Gao, J., Capared, S., and Chang, Z. 2014. Leaching of heavy metals from fast pyrolysis residues produced from different particle sizes of sewage sludge. *J. Anal. Appl. Pyrol.* 109: 168-175.

Jones, D.L., Rousk, J., Edwards-Jones, G., DeLuca, T.H., and Murphy, D.V. 2012. Biochar-mediated changes in soil quality and plant growth in a three year field trial. *Soil Biol. Biochem.* 45: 113-124.

Kampa, M. and Castanas, E. 2008. Human health effects of air pollution. *Environ. Pollut.* 151(2): 362-367.

Kan, T., Strezov, V., and Evans, T.J. 2016. Lignocellulosic biomass pyrolysis: A review of product properties and effects of pyrolysis parameters. *Renewable Sustain. Energy Reviews* 57: 1126-1140.

Karim, A.A., Kumar, M., Mohapatra, S., Panda, C.R., and Singh, A. 2015. Banana peduncle biochar: characteristics and adsorption of hexavalent chromium from aqueous solution. *Intr. Res. J. Pure Applied Chem.* 7(1): 123-132.

KAU [Kerala Agricultural University] 2016. *Package of Practices Recommendations: Crops* (15th Ed.). Kerala Agricultural University, Thrissur, 393p.

Kistler, R. C., Widmer, F., and Brunner, P. H. 1987. Behavior of chromium, nickel, copper, zinc, cadmium, mercury, and lead during the pyrolysis of sewage sludge. *Environ. Sci. Technol.* 21:704-708

Klinghoffer, N. B., Castaldi, M. J., and Nzihou, A. 2015. Influence of char composition and inorganics on catalytic activity of char from biomass gasification. *Fuel.* 157: 37-47.

Kumar, R. and Chandrashekar, N. 2013. Study on chemical, elemental and combustion characteristics of Lantana camara wood charcoal. *J. Indian Acad. Wood Sci.* 10: 134-139.

163

Kumari, K.G.I.D., Moldrup, P., Paradelo, M., Elsgaard, L. and de Jonge, L.W. 2017. Effects of Biochar on Dispersibility of Colloids in Agricultural Soils. *J. Environ. Quality* 46(1): 143-152.

Kuppusamy, S., Thavamani, P., Megharaj, M., Venkateswarlu, K., and Naidu, R. 2016. Agronomic and remedial benefits and risks of applying biochar to soil: Current knowledge and future research directions. *Environ. Int.* 87:1-12.

Laird, D. A., Fleming, P., Davis, D. D., Horton, R., Wang, B., and Karlen, D. L. 2010. Impact of biochar amendments on the quality of a typical midwestern agricultural soil. *Geoderma.* 158: 443-449.

Lawrinenko, M. and Laird, D.A. 2015. Anion exchange capacity of biochar. *Green Chem.* 17: 4628-4637.

Lee, J., Kim, K.H., and Kwon, E.E. 2017. Biochar as a catalyst. *Renewable Sustain. Energy Rev.* 77: 70-79.

Lee, Y., Park, J., Ryu, C., Gang, K. S., Yang, W., Park, Y. K., Jung, J. and Hyun, S. 2013. Comparison of biochar properties from biomass residues produced by slow pyrolysis at 500°C. *Bioresource Technol*. 148: 196-201.

Lehmann, J. 2007. A Handful of Carbon. *Nature.* 447: 143-144.

Lehmann, J. and Joseph, S. 2009. Biochar systems. In: Lehmann, J. and Joseph, S. (eds), *Biochar for environmental management*. Science and Technology, Earthscan, London. pp. 147-168.

Lehmann, J., da Silva Jr, J.P., Rondon, M., Cravo, M.D.S., Greenwood, J., Nehls, T., Steiner, C., and Glaser, B. 2002. August. Slash-and-char–a feasible alternative for soil fertility management in the central Amazon. In *Proceedings of the 17th World Congress of Soil Science* pp. 1-12.

Lehmann, J., da Silva, J. P., Steiner, C., Nehls, T., Zech, W., and Glaser, B. 2003. Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol in the Central Amazon basin: Fertiliser, manure and charcoal amendments. *Plant Soil.* 249: 343-357.

Lehmann, J., Kuzyakov, Y., Pan, G., and Ok, Y.S. 2015. Biochars and the plant-soil interface. *Plant Soil* 395: 1-5.

Lenhard, G. 1956. The dehydrogenase activity in soil as a measure of the activity of soil microorganisms. *Z. Pflanzenernaehr. Dueng. Bodenkd.* 73:1-11.

Liang, B., Lehmann, J., Solomon, D., Kinyangi, J., Grossman, J., O'Neill, B., Skjemstad, J. O., Thies, J., Luizao, F. J., Petersen, J., and Neves, E. G. 2006. Black carbon increases cation exchange capacity in soils. *Soil Sci. Soc. Am. J.* 70: 1719-1730.

Liu, J., Schulz, H., Brandl, S., Miehtke, H., Huwe, B., and Glaser, B. 2012. Short-term effectof biochar and compost on soil fertility and water status of a Dystric Cambisolin NE Germany under field conditions. *J. Plant Nutr. Soil Sci.* 175: 698-707.

Liu, Q., Wang, S.R., Zheng, Y., Luo, Z.Y., and Cen, K.F. 2008. Mechanism study of wood lignin pyrolysis by using TG-FTIR analysis. *J. Anal. Appl. Pyrol.* 82: 170-177.

Liu, Z. and Balasubramanian, R. 2014. A comparative study of nitrogen conversion during pyrolysis of coconut fiber, its corresponding biochar and their blends with lignite. *Bioresource Technol.* 151: 85-90.

Loow, Y. L., Wu, T. Y., Tan, K.A., Lim, Y.S., Siow, L.F., Jahim, J. M., Mohammad, A.W., and Teoh, W. H. 2015. Recent advances in the application of inorganic salt pretreatment for transforming lignocellulosic biomass into reducing sugars. *J. Agric. Food Chem.* 63(38): 8349-8363.

Lu, T., Yuan, H., Wang, Y., Huang, Y., and Chen, Y. 2015. Characteristic of heavy metals in biochar derived from sewage sludge. *J. Mater. Cycles Waste Manag.* 18(4): 725-733.

Major, J., Lehmann, J., Rondon, M., and Goodale, C. 2010b. Fate of soil applied black carbon: downward migration, leaching and soil respiration. *Glob. Chang. Biol.* 16: 1366–1379.

Major, J., Rondon, M., Molina, D., Riha, S. J., and Lehmann, J. 2010a. Maize yield and nutrition during 4 years after biochar application to a Colombian savanna oxisol. *Plant Soil.* 333: 117-128.

Major, J., Steiner, C., Downie, A., and Lehmann, J. 2009. Biochar Effects on Nutrient Leaching (Chapter 15), In: Lehmann, J. and Joseph, S. (eds.), *Biochar for Environmental Management: Science and Technology*, Earthscan, London, UK. 271p.

Mandal, S., Singh, R.K., Kumar, A., Verma, B.C., and Ngachan, S. V. 2013. Characteristics of Weed Biomass-derived Biochar and Their Effect on Properties of Beehive Briquettes. *Indian J. Hill Farming* 26: 8-12.

Massoumi, A. and Cornfield, A.H. 1963. A rapid method for determination of sulphate in water extracts of soil. *Analyst* 88: 321-322.

Masto, R. E., Ansari, M. A., George, J., Selvi, V. A., and Ram, L. C. 2013. Co-application of biochar and lignite fly ash on soil nutrients and biological parameters at different crop growth stages of *Zea mays*. *Ecol. Eng.* 58: 314-322.

Masulili, A., Utomo, W. H., and Syechfani, M. S. 2010. Rice husk biochar for rice based cropping system in acid soil 1. The characteristics of rice husk biochar and its influence on the properties of acid sulfate soils and rice growth in West Kalimantan, Indonesia. *J. Agric. Sci.* 2(1): 39-47.

Mohan, D., Kumar, A., and Pittman, C.U. 2016. Sustainable Biochar- A Tool for Climate Change Mitigation, Soil Management and Water and Wastewater Treatment. In: *Geostatistical and Geospatial Approaches for the Characterization of Natural Resources in the Environment*. Springer, Cham. pp. 949-952

Mundike, J., Collard, F.X., and Görgens, J.F. 2017. Pyrolysis of Lantana camara and Mimosa pigra: Influences of temperature, other process parameters and incondensable gas evolution on char yield and higher heating value. *Bioresource Technol*. 243: 284-293.

Muradov, N., Fidalgo, B., Gujar, A. C., Garceau, N., and Ali, T. 2012. Production and characterization of Lemna minor bio-char and its catalytic application for biogas reforming. *Biomass Bioenergy* 42: 123-131.

Nagodavithane, C.L., Singh, A.B., and Fang, Y. 2014. Effect of ageing on surface charge characteristics and adsorption behaviour of cadmium and arsenate in two contrasting soils amended with biochar. *Soil Res*. 52: 155-163.

Nigussie, A., Kissi, E., Misganaw, M., and Ambaw, G. 2012. Effect of biochar application on soil properties and nutrient uptake of lettuces (Lactuca sativa) grown in chromium polluted soils. *American-Eurasian J. Agricultural Environ. Sci.* 12(3): 369-376.

Novak, J. M., Busscher, W. J., Laird, D. L., Ahmedna, M., Watts, D. W., and Niandou, M. A. S. 2009. Impact of biochar amendment on fertility of a Southeastern coastal plain soil. *Soil Sci.* 174: 105-112.

Novak, J. M., Busscher, W. J., Watts, D. W., Woodroof, R. H., Lima, I. M., Ahmeda, M., Rehrah, D., and Xing, B. 2012. Influence of biochar on nitrogen fractions in a coastal plainsoil. *J. Environ. Qual.* 41: 1087-1095.

Oleszczuk, P., Jośko, I., Futa, B., Pasieczna-Patkowska, S., Pałys, E., and Kraska, P. 2014. Effect of pesticides on microorganisms, enzymatic activity and plant in biochar-amended soil. *Geoderma* 214: 10-18.

Pandian, K., Subramaniayan, P., Gnasekaran, P., and Chitraputhirapillai, S. 2016. Effect of biochar amendment on soil physical, chemical and biological properties and groundnut yield in rainfed Alfisol of semi-arid tropics. *Archives Agron. Soil Sci.* 62(9): 1293-1310

Pappu, A., Saxena, M., and Asolekar, S.R. 2007. Solid wastes generation in India and their recycling potential in building materials. *Build Environ.* 42: 2311-2320.

Peters, J. F., Iribarren, D., and Dufour, J. 2015. Biomass pyrolysis for biochar or energy applications? A life cycle assessment. Environ. *Sci. Technol.* 49(8): 5195-5202.

Piper, C.S. 1966. Aging of crystalline precipitates. *Analyst.* 77: 1000-1011.

Piper, C.S. 1967. *Soil and Plant Analysis*. Asia Publishing House, Bombay. 368 p.

Prabha, V. S., Renuka, R., Sreekanth, N. P., Padmakumar, B., and Thomas, A. P. 2013. A study of the fertility and carbon sequestration potential of rice soil with respect to the application of biochar and selected amendments. *Annals Environ. Sci. J.* 7: 17-30.

Qu, T.T., Guo, W.J., Shen, L.H., and Xiao, J. 2011. Zhao K. Experimental study of biomass pyrolysis based on three major components: hemicellulose, cellulose, and lignin. *Ind. Eng. Chem. Res.* 50: 424-433.

Radlein, D., Piskorz, J. K., and Majerski, P. 1996. Method of producing slow release nitrogenous organic fertilizer from biomass. *Eur. Pat. Appl.* 0716056: A1.

Rajkovich, S., Enders, A., Hanley, K., Hyland, C., Zimmerman, A.R. and Lehmann, J. 2011. Corn growth and nitrogen nutrition after additions of biochars with varying properties to a temperate soil. *Biol. Fertil. Soils*. DOI 10.1007/s00374-011-0624-7. Published Online [18 March 2013].

Ranganna, S. 1977. Manual of Analysis of Fruit and Vegetable Products, Tata McGraw-Hill Education, New York, 634 p.

Raveendran, K., Ganesh, A., Khilar, K.C., 1995. Influence of mineral matter on biomass pyrolysis characteristics. Fuel 74, 1812-1822.

Reed, T. and Das, A., 1988. *Handbook of biomass downdraft gasifier engine systems*. Biomass Energy Foundation. 140p.

Roig A., Lax A., Cegarra J., Costa P. and Hernandez M.T. 1988. Cation exchange capacity as a parameter for measuring the humification degree of manures. *Soil Sci.* 146(5): 311-316.

Rondon, M. A., Lehmann, J., Ramirez, J., and Hurtado, M. 2007. Biological nitrogen fixation by common beans (*Phaseolus vulgaris* L.) increases with bio-char additions. *Biol. Fertil. Soils*. 43: 699-708.

Sarma, B., Borkotoki, B., Narzari, R., Kataki, R. and Gogoi, N., 2017. Organic amendments: Effect on carbon mineralization and crop productivity in acidic soil. *J. Cleaner Prod.* 152: 157-166.

Schmalenberger, A. and Fox, A. 2016. Bacterial mobilization of nutrients from biochar amended soils. *Adv. Appl. Microbiol.* 94: 109-9.

Schmidt, H. P., Taylor, P., and Kon-Tiki. 2014. Flame curtain pyrolysis for the democratization of biochar production. *Biochar J.* 1: 14-24.

Shafizadeh, F. 2014. The chemistry of pyrolysis and combustion. *Advan. Chem.* 207: 489-529

Shenbagavalli, S. and Mahimairaja, S. 2012. Production and characterization of biochar from different wastes. *Int. J. Pl. Animal Environ. Sci*. 2: 197-201.

Siddiqui, A.R., Nazeer, S., Piracha, M.A., Saleem, M.M., Siddiqi, I., Shahzad, S.M. and Sarwar, G. 2016. The production of biochar and its possible effects on soil properties and phosphate solubilizing bacteria. *J. Applied Agric. Biotechnol.* 1(1): 27-40.

Sika, M. P. 2012. *Effect of biochar on chemistry, nutrient uptake and fertilizer mobility in sandy soil*. M. Sc thesis, University of Stellenbosch. 123p.

Sims, J.T. and Johnson, G.V. 1991. *Micronutrients in Agriculture.* Soil Science Society of America, Madison, USA, 50p.

Sohi, S. P., Krull, E., Lopez-Capel, E., and Bol, R. 2010. Chapter 2-A review of biochar and its use and function in soil. *Adv. Agron.* 105: 47-82.

Sohi, S.P. 2012. Agriculture. Carbon storage with benefits. *Science* 338(6):1034-1035.

Soinne, H., Hovi, J., Tammeorg, P., and Turtola, E. 2014. Effect of biochar on phosphorous sorption and clay soil aggregate stability. *Geoderma* 219: 162-167.

Sokchea, H., Borin, K., and Preston, T. R. 2013. Effect of biochar from rice husks (combusted in a downdraft gasifier or a paddy rice dryer) on production of rice fertilized with biodigester effluent or urea. *Livest. Res. Rural Develop.* 25: 64-66.

Southavong, S. and Preston, T.R. 2011. Growth of rice in acid soils amended with biochar from gasifier or TLUD stove, derived from rice husks, with or without biodigester effluent. *Livest. Res. Rural Develop.* 23: 32-35.

Southavong, S., Pretson, T.R., and Man, N.V. 2012. Effect of biochar and biodigester effluent on growth of water spinach (*Ipomoea aquatic*) and soil fertility. *Livest. Res. Rural Develop.* 24: 41-46.

Sparks, D. L. 2003. Environmental Soil Chemistry. Academic Press, San Diego, CA, USA. 430p.

Sparrevik, M., Adam, C.,Martinsen, V., Jubaedah, J., and Cornelissen, G. 2015. Emissions of gases and particles from charcoal/biochar production in rural areas using medium-sized traditional and improved "retort" kilns. *Biomass Bioenergy* 72: 65-73.

Spokas, K.A., Cantrell, K.B., Novak, J.M., Archer, D.W., Ippolito, J.A., Collins, H. P., Boateng, A.A., Lima, I.M., Lamb, M.C., McAloon, A.J., Lentz, R.D., and Nichols, K.A. 2012. Biochar: a synthesis of its agronomic impact beyond carbon sequestration. *J. Environ. Qual.* 41: 973–989.

Stavi, I. and Lal, R. 2013. Agro forestry and biochar to offset climate change: a review. *Agron. Sustain. Dev.* 33: 81-96.

Steiner, C. 2007. Soil charcoal amendments maintain soil fertility and establish a carbon sink-research and prospects. *Soil Eco. Rese. Dev.*: 1–6.

Steiner, C., Teixeira, W.G., Lehmann, J., Nehls, T., de Macedo, J.L.V., Blum, W.E. H., and Zech, W. 2007. Long term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered Central Amazonian upland soil. *Plant Soil* 291 (12): 275-290.

Stover, R.H. and Simmonds, N.W. 1987. *Bananas* (3rd Ed.). Longman Scientific and Technical, New York, Wiley, 468 p.

Subbiah, B. V. and Asija, G. I. 1956. A rapid procedure for estimation of available nitrogen in soil. *Curr. Sci.* 25: 258-260

Sugumaran, P. and Seshadri, S. 2009. Evaluation of selected biomass for charcoal production. J Sci Ind Res 68(8):719–723

Sukartono, L., Umoto, W.H., Kusuma, Z. and Nugroho, W.H. 2011. Soil fertility status, nutrient uptake and maize yield following biochar and cattle manure application on sandy soils of Lombok, Indonesia. *J. Trop. Agric.* 49: 47-52.

Tabatabai, M. A. 1982. Sulfur. In: Page, A.L. (ed.), *Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties, Agronomy Monograph 9.2* (2nd Ed.). ASA-SSSA, Madison, USA, pp. 501-538.

Tammeorg, P., Simojoki, A., Mäkelä, P., Stoddard, F., Alakukku, L., and Helenius, J. 2014. Biochar application to a fertile sandy clay loam in boreal conditions: effects on soil properties and yield formation of wheat, turnip rape and faba bean. *Plant Soil* 374: 89-107.

Thies, J. E. and Rillig, M. C. 2009. Characteristics of Biochar - Biological Properties (Chapter 6). In: Lehmann, J. and Joseph, S. (eds.), *Biochar for Environmental Management: Science and Technology*, Earthscan, London, UK, 85p.

Thies, J. E., Rillig, M. C., and Graber, E. R. 2015. Biochar effects on the abundance, activity and diversity of the soil biota. In: J. Lehmann, S. Joseph (eds.) Biochar for environmental management: science, technology and implementation, 2nd ed. Routledge, Abingdon, UK, pp. 327-390.

Thompson, K. A., Shimabuku, K. K., Kearns, J. P., Knappe, D. R., Summers, R. S., and Cook, S. M. 2016. Environmental comparison of biochar and activated carbon for tertiary wastewater treatment, *Environ. Sci. Technol.* 50 (20): 11253-11262.

Topoliantz, S., Ponge, J. F., Arrouays, D., Ballof, S., and Lavelle, P. 2002. Effect of organic manure and the endogeic earthworm *Pontoscolex corethrurus* (Oligochaeta: Glossoscolecidae) on soil fertility and bean production. *Biol. Fertil. Soils.* 36: 313-319.

Turner, B. L., Frossard, E., and Oberson, A. 2006. Enhancing phosphorus availability in low-fertility soils. In: Uphoff, N., Ball, A., Fernandes, E., Herren, H., Husson, O., Laing, M., Palm, C., Pretty, J., Sanchez, P., Sanginga, N. and Thies, J. (eds.). *Biological approaches to sustainable soil systems.* CRC Press: Taylor & Francis Group. pp. 191-205.

Uddin, M.N., Daud, W.M.A.W., and Abbas, H.F. 2014. .Effects of pyrolysis parameters on hydrogen formations from biomass: a review. *RSC. Adv.* 4: 10467-10490.

Vaccari, P. F., Baronti, S., Lugatoa, E., Genesio, L., Castaldi, S., and Fornasier, F. 2011. Biochar as a strategy to sequester carbon and increase yield in durum wheat. *Eur. J. Agron.* 34: 231–238.

Van Zwieten, L., Kimber, S., Morris, S., Chan, K. Y., Downie, A., Rust, J. Joseph S., and Cowie, A. 2010. Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility. *Pl. Soil*. 327: 235–246.

Van Zwieten, L., Rose, T., Herridge, D., Kimber, S., Rust, J., Cowie, A., and Morris, S. 2015. Enhanced biological N2 fixation and yield of faba bean (*Vicia faba* L.) in an acid soil following biochar addition: dissection of causal mechanisms. *Plant Soil*: 1-14.

Vasujini, P., Dandeniya, W.S. and Dharmakeerthi, R.S., 2014. An Assessing of the Quality of Biochar Produced from Coconut Husk Waste. *J. Soil Sci. Soc. Sri Lanka*, 3: 21-32.

Venkatesh, G., Venkateshwarlu, B., Gopinath, K.A., Srinivas, C., and Korwar, G.R. 2013. Low-cost portable kiln for biochar production. NICRA Technical Brochure, Hyderabad.

Verheijen, F. G. A., Jeffery, S., Bastos, A. C., Velde, M., and Diafas, I. 2010. Biochar application to soils - A critical scientific review of effects on soil properties, processes and functions. Rep. EUR 24099 EN. Office for the Official Publications of the European Communities, Luxembourg. Available online [12-March-2013]

Wabel, M. I. A., Omran, A. A., Naggar, A H. E., Nadeem, M., and Usman, A. R. A. 2013. Pyrolysis temperature induced changes in characteristics and chemical composition of biochar produced from conocarpus wastes. *Bioresource Technol*. 131: 374-379.

Walkley, A. and Black, I. A. 1934. An examination of the Degtareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Sci*. 37: 29-38.

Wang, S., Wang, H., Yin, Q., Zhu, L., and Yin, S. 2014. Methanation of bio-syngas over a biochar supported catalyst. *New J. Chem.* 38: 4471-4477.

Wei, B. and Yang, L. 2010. A review of heavy metal contaminations in urban soils, urban road dusts and agricultural soils from China. *Microchem.* 94(2): 99-107.

White, J.E., Catallo, W.J., Legendre, and B.L. 2011. Biomass pyrolysis kinetics: a comparative critical review with relevant agricultural residue case studies. *J. Anal. Appl. Pyrol.* 91: 1-33.

Whitman, T. and Lehmann, J. 2009 Biochar-One way forward for soil carbon in offset mechanisms in Africa. *Environ. Sci. Policy* 12: 1024-1027.

Widowatil, W. and Asnah, A. 2014. Biochar Can Enhance Potassium Fertilization Efficiency and Economic Feasibility of Maize Cultivation. *J. Agric. Sci.* 6(2): 24-36.

Xiong, S., Zhang, S., Wu, Q., Guo, X., Dong, A., and Chen, C. 2014. Investigation on cotton stalk and bamboo sawdust carbonization for barbecue charcoal preparation. *Bioresour. Technol*. 152, 86-92.

Yan, Q., Wan, C., Liu, J., Gao, J., Yu, F., Zhang, J., and Cai, Z. 2013. Iron nanoparticles in situ encapsulated in biochar-based carbon as an effective catalyst for the conversion of biomass derived syngas to liquid hydrocarbons. *Green Chem.* 15: 1631-1640.

Zhang, A., Cui, L., Pan, G., Li, L., Hussain, Q., Zhang, X., Zheng, J., and Crowley, D. 2010. Effect of biochar amendment on yield and methane and nitrous oxide emissions from a rice paddy from Tai lake plain, china. *Agric. Ecosyst. Environ.* 139: 469-475.

Zhang, C., Liang, X., and Liu, S. 2011. Hydrogen production by catalytic dehydrogenation of methyl cyclohexane over Pt catalysts supported on pyrolytic waste tire char. *Int. J. Hyd. Energy* 36: 8902-8907.

Zheng, R., Chen, Z., Cai, C., Wang, X., Huang, Y., Xiao, B., and Sun, G. 2013. Effect of biochars from rice husk, bran, and straw on heavy metal uptake by pot-grown wheat seedling in a historically contaminated soil. *Bio Resources* 8(4): 5965-5982.

Zheng, W., Guo, M.X., Chow, T., Bennett, D.N., and Rajagopalan, N. 2010. Sorption properties of greenwaste biochar for two triazine pesticides. *J. Hazardous Mat*. 181: 121-126.

Zimmerman, A.R. 2010. Abiotic and microbial oxidation of laboratory produced black carbon (biochar). *Environ. Sci. Technol.* 44: 1295-1301.

ABSTRACT

TECHNOLOGY REFINEMENT FOR BIOCHAR PRODUCTION AND EVALUATION OF ITS EFFECT ON SOIL HEALTH AND CROP PRODUCTIVITY

by

SAINATH NAGULA

(2014-21-134)

Abstract of the thesis

Submitted in partial fulfilment 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
VELLAYANI, THIRUVANANTHAPURAM - 695 522
KERALA, INDIA
2017

ABSTRACT

A study entitled ‘Technology refinement for biochar production and evaluation of its effect on soil health and crop productivity’ was carried out at the Department of Soil science and Agricultural Chemistry, College of Agriculture, Vellayani, during March 2015 to June 2016. The objective of the study was refinement of technology for micro level biochar production from tender coconut husk and evaluation of its effect on soil health, yield and quality of banana (*Musa* spp.) in the field.

A modified design of micro biochar kiln for the pyrolysis of tender coconut husk to biochar was developed. The micro kiln consists of a temperature monitoring enabled, double barrel reactor unit with chimney and a cooling assembly for condensation and cooling of syngas. The reactor unit had a biomass capacity of 30 kg. The pyrolytic conversion happened at temperature >350 °C and time required was 90 minutes. Characterization of biochar produced was done by standard procedures and it had an alkaline pH (8.53), CEC (15.26 cmol kg^{-1}), AEC (5.64 cmol kg^{-1}), C: N (46.11), C:P (175.25), C:S (259.62) and C:N:P:S (350:7.5:2:1) ratios. Electrical Conductivity, total C, N, P, K, Ca, Mg, S, Fe, Mn and B were 1.70 dS m^{-1}, 70.10 %, 1.52 %, 0.40 %, 2.26 %, 0.54 %, 0.46 %, 0.27 %, 89.9 mg kg^{-1}, 2.84 mg kg^{-1} and 6.78 mg kg^{-1} respectively. The heavy metal contents (Pb, Cd, Ni, Cr, Zn and Cu) were very low when compared to the maximum allowed threshold levels. The syngas produced during pyrolysis was analyzed by gas chromatography and its composition was carbon dioxide (67.70%), methane (22.89%), oxygen (8.74%), hydrogen (0.66%) and n-Butane (0.001%) on normal mol % (dry) basis. Carbon monoxide and nitrogen were absent. The biochar recovery percentage was 50 %, which was 17 % more than the previous model of biochar kiln. The quantity of syngas produced was comparatively less. The composition of syngas produced revealed that it can not be used as a bioenergy source because the methane content is less. There was no production of bio oil during

pyrolysis. All these advantages qualifies this refined technology as the most effective in carbon sequestration and safe waste management.

In order to find out the effect of biochar on soil health and crop productivity, a field experiment was carried out with nendran banana as test crop in Loamy, Kaolinitic, Isohyperthermic, Typic Kandiustults belonging to Vellayani series. Treatment combinations were T_1- Package of practices recommendation, T_2- BC @ 5 kg plant^{-1} + NPK as per POP, T_3- BC @ 10 kg plant^{-1} + NPK as per POP, T_4- BC @ 5 kg plant^{-1} + 75% NPK as per POP, T_5- BC @ 10 kg plant^{-1} + 75% NPK as per POP, T_6- FYM 10 kg plant^{-1} + (NPK + secondary and micronutrients as per Soil test based recommendation), T_7- BC @ 5 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR), T_8- BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR), T_9- BC @ 5 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR), T_{10}- BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) and T_{11}- BC alone 10 kg plant^{-1}.

Plant biometric characters like plant height at 2, 4, 6 and 8 months after planting, number of leaves per plant at 2 and 6 MAP and pseudostem girth at 4 and 8 MAP were highest in the treatment (T_{10}) where biochar @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR) was applied followed by 5 kg biochar + 75% of NPK as per POP (T_4). The total dry matter production was significantly higher with biochar @ 10 kg plant^{-1}+ 75 % of STBR. Biochar @ 10 kg plant^{-1} added with 75% of STBR resulted in the highest bunch weight, number of hands per bunch, number of fingers per bunch and both length and girth of the index finger. 10 kg biochar along with 75% STBR enhanced the physical properties of the soil by imparting 57.11 % increase in the WHC, 35.32 % increase in porosity and 7.31 % decrease in the bulk density than application with FYM + NPK as per POP. A significant increase in soil pH was observed in the biochar based treatments as compared to the FYM applied treatments with a 0.6 units increase in pH in the treatment which received 10 kg biochar

+ 75% STBR. The highest OC content of 1.45 % and a 100 % increase in CEC of the soil was realized when biochar @ 10 kg along with 75 % of STBR were applied instead of FYM based POP recommendation. The biochar application @ 10 kg with 75 % of STBR significantly increased the soil available N, K, Mg and B at the active growth and harvest stages of banana. Zn content was highest in this treatment throughout all stages. The superiority of biochar based treatments as compared to FYM based treatments in promoting the growth and development of soil microorganisms in the rhizosphere was evident with a 55.9 % enhancement in soil dehydrogenase activity in the treatment where biochar @ 10 kg plant^{-1} + 75% STBR was applied.

Biochar @ 10 kg plant^{-1} with 75 % STBR (T_{10}) recorded highest foliar N, K, Mg, S, Fe, Mn, Zn content, as well as highest nutrient use efficiency of 50.4 %. Fruit quality parameters like TSS, ascorbic acid content and shelf life of fruits were found to be superior for the same treatment. The highest B:C ratio of 2.38 was also found in T_{10} treatment. Based on this a biochar based nutrient mix was prepared by mixing 10 kg biochar with urea $_{260.21g}$, MOP $_{528.75g}$ and $MgSO_4$ $_{23.44g}$ for Typic Kandiustults of Vellayani series.

Hence it may be concluded that the biochar produced by modified micro biochar kiln had ideal physical and chemical properties that qualify it to be used as a good soil amendment which is environmentally safe and contributing to the soil carbon pool. Biochar application in general, and biochar (10 kg plant^{-1}) along with 75 % soil test based recommendation in particular, enhanced the soil physical properties, decreased soil acidity, promoted rhizospheric microorganisms, increased the soil fertility status enabling efficient nutrient use and resulted in higher growth, profitable yield and superior fruit quality of banana.

APPENDICES

Appendix-I

Weather parameters during the cropping period (September 2015 to June 2016)

Month and year	Temperature (^{0}C)		Relative Humidity (%)	Rainfall (mm)
	Maximum	Minimum		
September, 2015	31.4	24.4	88.0	289.8
October, 2015	31.3	24.0	86.5	399.1
November, 2015	31.5	23.8	86.1	254.1
December, 2015	31.5	23.4	88.5	259.3
January, 2016	32.5	22.6	81.9	0.4
February, 2016	32.9	23.2	82.9	43.6
March, 2016	34.4	24.6	79.3	1.9
April, 2016	35.3	26.6	83.9	22.6
May, 2016	33.8	25.4	83.0	463.3
June, 2016	31.5	24.4	88.7	14.7

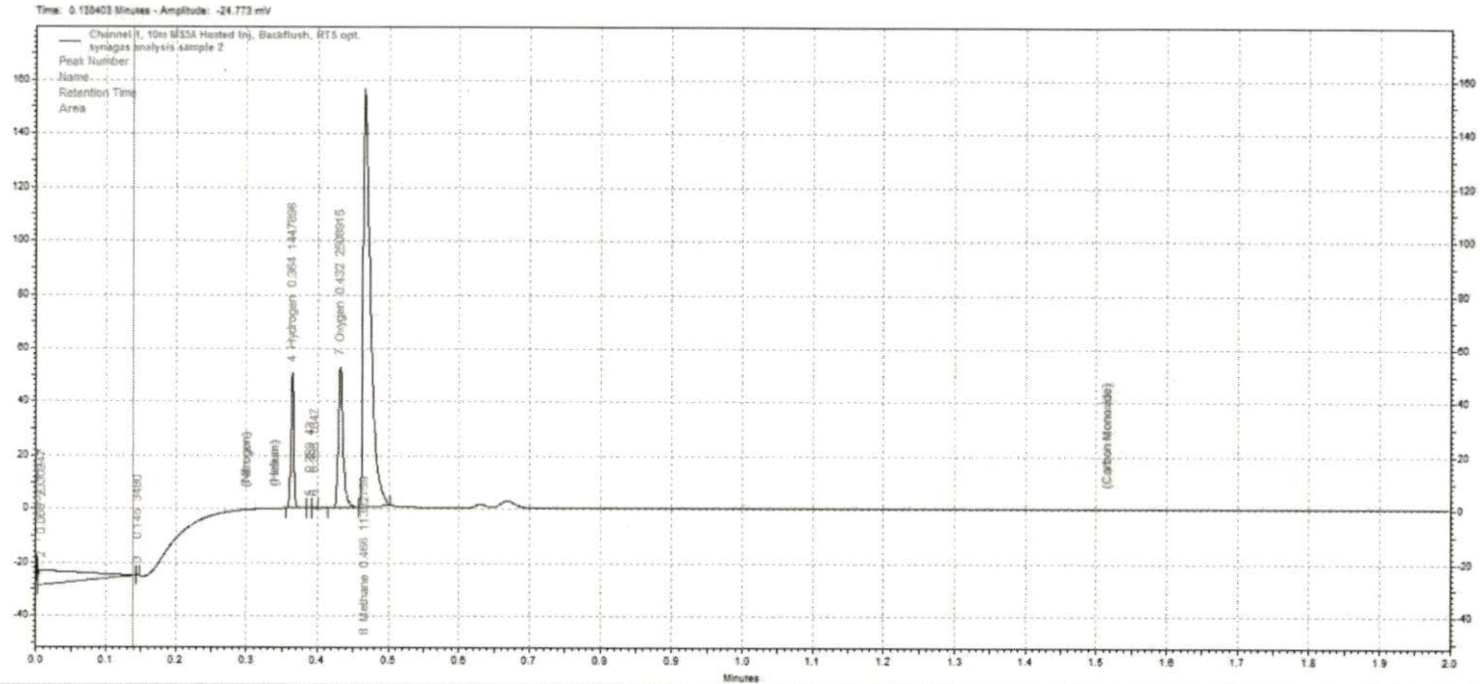
Appendix-II

Effect of treatments on total cost, gross income and net returns

Treatments	Total cost (Rs ha^{-1})	Gross income (Rs ha^{-1})	Net returns (Rs ha^{-1})
T_1- Package of practices recommendation	616065.0	807300	191235.0
T_2- BC @ 5 kg plant^{-1} + NPK as per POP	626065.0	912600	286535.0
T_3- BC @ 10 kg plant^{-1} + NPK as per POP	491884.6	897000	405115.5
T_4- BC @ 5 kg plant^{-1} + 75% NPK as per POP	501515.5	1058200	556684.5
T_5- BC @ 10 kg plant^{-1} + 75% NPK as per POP	495441.6	887900	392458.5
T_6- FYM 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	471360.0	955500	484140.0
T_7- BC @ 5 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	423860.0	826800	402940.0
T_8- BC @ 10 kg plant^{-1} + (NPK + secondary & micronutrients as per STBR*)	471360.0	912600	441240.0
T_9- BC @ 5 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	510263.8	1011400	501136.3
T_{10}- BC @ 10 kg plant^{-1} + 75% (NPK + secondary & micronutrients as per STBR*)	498863.8	1188200	689336.3
T_{11}- BC alone 10 kg plant^{-1}	553700.0	707200	153500.0

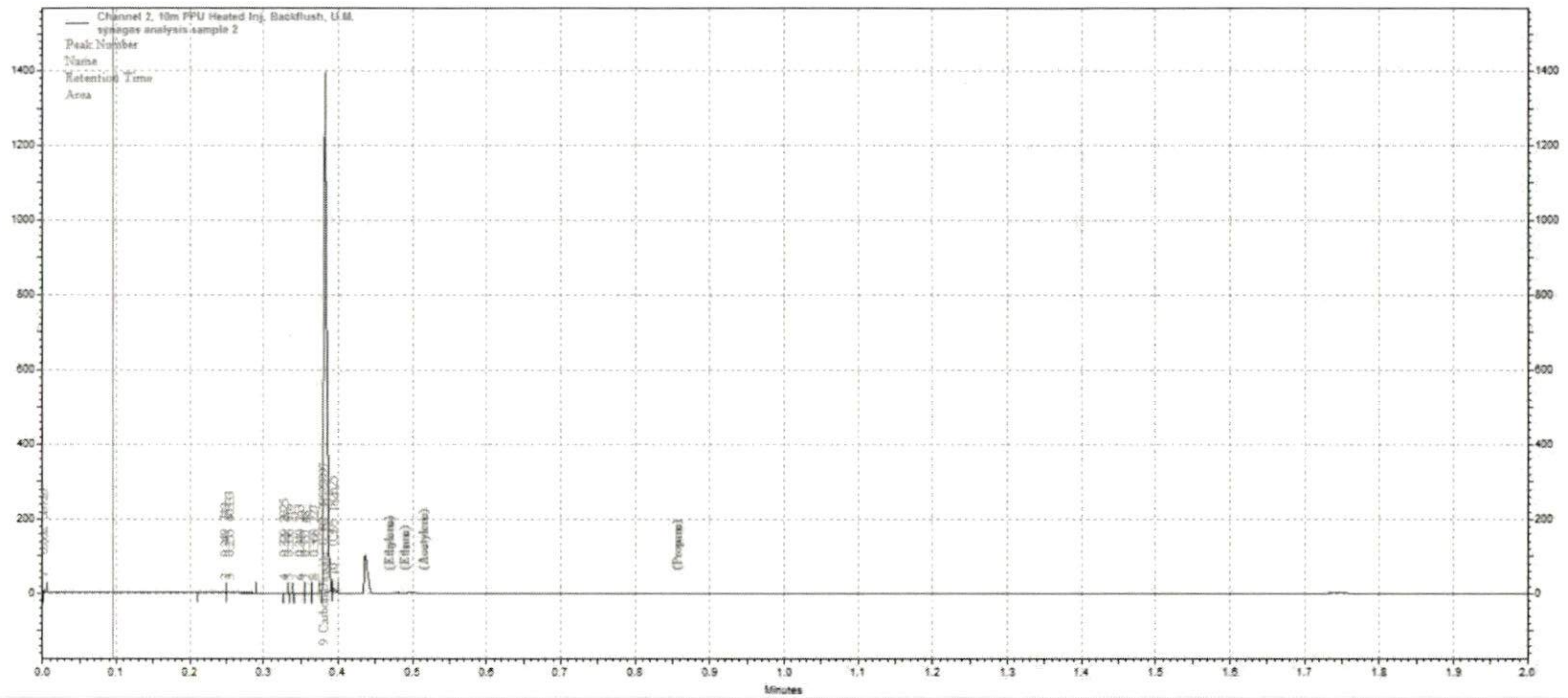
*BC-Biochar, FYM-Farm yard manure, STBR-Soil test based recommendation

Appendix-III A



174083

Appendix-III B



A and B. Composition of syngas analyzed using a micro gas chromatograph