Science Journal of Analytical Chemistry
2025, Vol. 13, No. 1, pp. 1-8
https://doi.org/10.11648/j.sjac.20251301.11

Research Article

Integrated Use of Biochar and Lime Enhances Soil Properties and Maize Yield in Acidic Soil of Jimma Zone, Southwestern Ethiopia

Bikila Takala[1,*], Ewnetu Teshale[2], Adugna Bayata[2]

[1]Ethiopian Institute of Agricultural Research, Holata Agricultural Research Center, Holata, Ethiopia
[2]Ethiopian Institute of Agricultural Research, Jimma Agricultural Research Center, Jimma, Ethiopia

Abstract

Due to continuous cultivation high soil acidity, low nutrient inputs and soil fertility depletion has been a major threat to maize crop production and productivity in Jimma area, Southwestern Ethiopia. Recently, biochar has emerged as a soil amendment to improve and maintain soil health and enhance soil carbon sequestration. Thus, the experiment was conducted in 2017/18 and 2018/19 cropping seasons with the objective of generating information on the effects of Bio-char and their interactions with lime and inorganic fertilizers on crop productivity and properties of acid soil at Kersa district, Jimma zone, Southwestern Ethiopia. Randomized Complete Block Design with three replications was used. The treatment design included: negative control (without any input), Recommended NP, Bio char at a rate of 10 t/ha (it is the recommended?), Bio char (10 t/ha) + Recommended NP, 50% Bio char (5 t/ha) + 50% Recommended NP, Bio char (10 t/ha) +Recommended lime (1.5 X EA), 50% Bio char +50% Recommended lime (1.5 X EA), Recommended NP + Recommended lime (1.5 X EA), and 50% Bio char + 50% Recommended NP + 50% Recommended lime. The biochar was applied one month before sowing and mixed thoroughly in the upper 15 cm soil depth. The lime ($CaCO_3$) treatments were broadcasted by hand and mixed thoroughly with soils one month before planting of the test crop. During the second season, the lime and Biochar treatments were not applied. The recommended NPSB fertilizer was applied based on the recommendation for maize crop to plot that receive NPSB fertilizer. The result of the experiment revealed that application of biochar alone and biochar with lime increased soil pH, available p, total N, and OC and decreased exchangeable acidity. The maximum mean grain yield of 6831.8 kg/ha was recorded from Bio char + Recommended NP plots. However, the treatment with the highest MRR (marginal rate of return) of 2868% was 50% Bio char + 50% Rec. NP + 50% Rec. lime with net benefit of (63994 ETB ha^{-1}).

Keywords

Biochar, Inorganic Fertilizer, Lime, Maize Yield, Soil Acidity

1. Introduction

Maize (*Zea mays* L.), also called corn, is the third most important cereal crop in the world after wheat and rice. In Ethiopia, it is the second most widely cultivated crop and is grown under diverse agro-ecologies and socioeconomic con-

*Corresponding author: biktak@gmail.com (Bikila Takala)

Received: 18 December 2024; **Accepted:** 31 December 2024; **Published:** 16 January 2025

Copyright: © The Author(s), 2025. Published by Science Publishing Group. This is an **Open Access** article, distributed under the terms of the Creative Commons Attribution 4.0 License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution and reproduction in any medium, provided the original work is properly cited.

ditions [18]. The major constraints affecting maize production and productivity are declining soil fertility and inadequate crop management practices, imbalance of nutrition, weed infestation, etc. [8]. Declining soil fertility is fundamental impediment to agricultural growth and a major reason for the slow growth in maize production in Sub-Saharan Africa. Soil acidity is now a serious threat to crop production in most highland areas of Ethiopia, in general, and in southern and western parts, in particular. About 43% of the total arable land of Ethiopia is affected by soil acidity [2]. The problem is considered to be one of the major bottlenecks to improve maize production in the country.

Integrated soil fertility management involving the judicious use of combinations of organic and inorganic resources is a feasible approach to overcome soil fertility constraints and contribute high crop productivity in agriculture [1]. In degraded and resource-limited cropping systems, the combined application of mineral fertilizers and organic inputs is a recommended practice for soil fertility and crop productivity enhancement. Recently, biochar has emerged as important soil amendment to improve and maintain soils health and enhance soil carbon sequestration. It is a fine-grained carbon rich and highly porous material that is produced from the thermal conversion (pyrolysis) of biomass in a low or no oxygen environment [12]. Application of biochar to acidic soil increases its sorption capacity for nutrients, reduces the exchangeable acidity, enable to adsorb or retain nutrients and water, and provides a habitat for beneficial microorganisms to flourish [13]. Biochar can function as a liming agent by causing an increase in soil pH and thus improving availability and uptake of nutrients by plants for various soil types [10]. Thus, the experiment was conducted with the objective of generating information on integrated organic and inorganic fertilizer management of acid soils for increasing the productions and productivity of maize in the southern and southwestern parts of Ethiopia. The specific objectives were: i) to the determine the effects of Bio char and their interactions with lime and inorganic fertilizers on maize productivity; ii) to the determine the effects of Bio char and their interactions with lime on selected soil chemical properties, iii) to determine the economic feasibility of integrated application of biochar and lime on acid soils.

2. Material and Methods

2.1. Description of the Study Area

The study was conducted at Kersa district, Jimma Zone, Oromia Regional State, Southwestern Ethiopia. Geographically, the district is located between 7°35′–8°00′N latitudes, 36°46′–37°14′E longitude. The altitude ranges from 1740 to 2660 m above sea level and consists of 10 percent dega, and 90 percent woinadega, agro ecologies. The main rainy season in Kersa area stretches from March to September and the area receives an average annual rainfall of 900-1300 mm. Temperatures range from 20-28℃ with variations across specific agro ecologies. Nitisols is the dominant soil type of the study area.

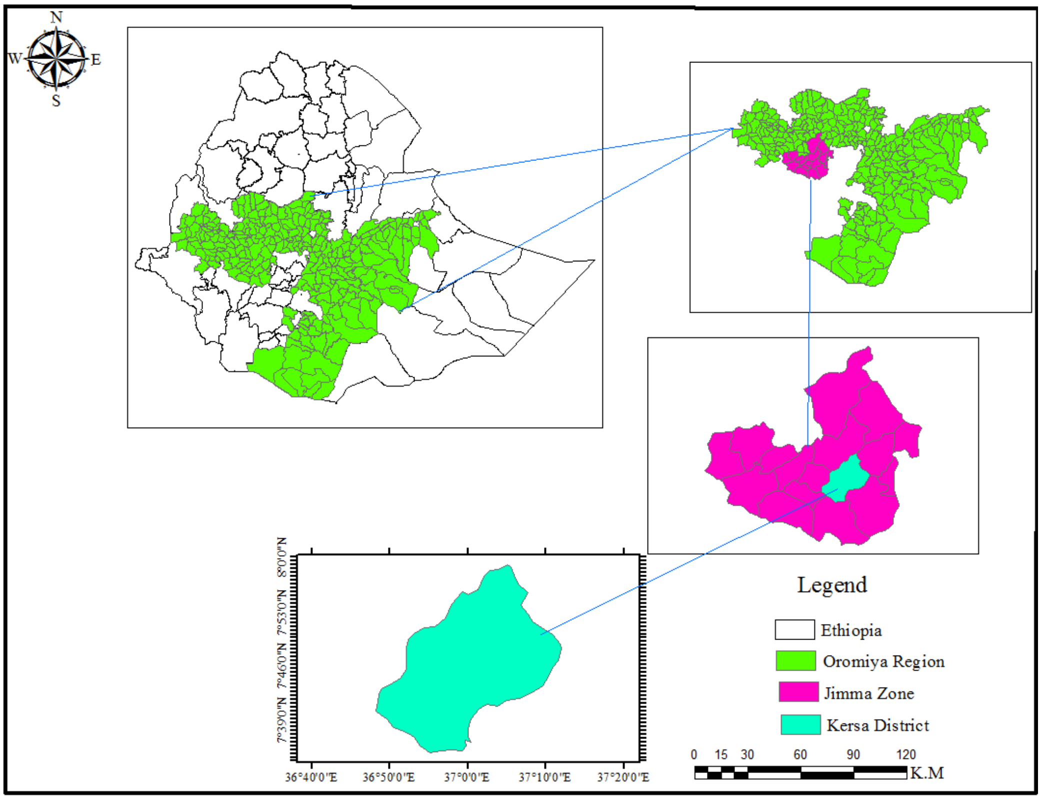

Figure 1. *Map of the study area, Kersa district.*

2.2. Experimental Design and Procedures

The experiment was conducted in 2017/18 and 2018/19 cropping season at Kersa district on farmers' field at two locations. The design of the experiment was RCBD (Randomized Complete Block Design) with 3 replications. The experiment consisted of 9 treatments: negative control (without any input), Recommended NP of the test crop, Bio char at a rate of 10 t/ha, Bio char (10 t/ha) + Recommended NP, 50% Bio char (5 t/ha) + 50% Recommended NP rate, Bio char (10 t/ha) +Recommended lime (1.5 X EA), 50% Bio char +50% Recommended lime (1.5 X EA), Recommended NP + Recommended lime (1.5 X EA), and 50% Bio char + 50% Recommended NP + 50% Recommended lime. Biochar was prepared from coffee husk and applied on a weight basis one month before sowing and mixed thoroughly in the upper 15 cm soil depth. The ($CaCO_3$) treatments were determined based on exchangeable acidity. The lime treatments were applied by hand broadcasted and mixed thoroughly with soils one month before planting. Permanent plots were used and treatment applications for the second season did not include lime and biochar. The recommended NPSB fertilizer was applied to the plots that receive NPSB fertilizer based on the recommendation for maize crop.

2.3. Soil Sampling and Analysis

Composite soil samples were collected before planting for site characterization. Plot level composite samples were collected after harvest from 20 cm soil depth. All samples were analysed for pH, available P, total N, organic carbon (OC), exchangeable acidity. Soil pH was determined by potentiometric methods at a 1:2.5 soil to water ratio [19]. Total N was analyzed using the Kjeldahl digestion, distillation and titration method [3]. Available phosphorus by Bray II method [4]. Exchangeable acidity was extracted using unbuffered 1M KCl. Exchangeable cations (Ca, Mg, K and Na) were determined after extracting the soil samples by 1N ammonium acetate solution at pH 7.0. Exchangeable Ca and Mg in the extract were measured by atomic absorption spectrophotometer (AAS), whilst K and Na determined using flame photometer [19]. The cation exchange capacity (CEC) was determined by ammonium acetate method at pH: 7 [5].

2.4. Data Analysis

All the relevant data was summarized and subjected to analysis of variance (ANOVA) using the General Linear Model of SAS 9.3 [16]. Treatment means were separated using LSD at 5% probability level. Partial budget analysis was carried out following [7] procedure based on local market price.

3. Result and Discussion

3.1. Effect of Biochar and Lime on Soil Properties

The results laboratory analysis of initial soil samples indicated that the soils are highly acidic with pHw values of 4.68 for site 1 and 4.36 for site 2. The exchange acidity was 1.2 for site and 2.01 Cmol+/kg soil for site 2. Available P was very low, 2.85 – 3.56 ppm, and total N varied from 1.12 – 1.15 %. The lab analysis of biochar showed very high pHw: 10.9 and available P content of 31.82 ppm (Table 1). Generally, the laboratory data showed that the capacity of biochar to increase soil pH and available soil P is very high, depending on the rates applied.

Table 1. *Descriptions of initial soil of the study area and biochar results.*

Parameters	Soil		Coffee husk Biochar
	Site 1	Site 2	
pH-H_2O (1:2.5)	4.68	4.36	10.95
Total N %	1.15	1.12	2.14
Available P. (mg /kg)	3.56	2.85	31.82
OC	1.2	1.08	
Exchangeable acidity	1.2	2.01	-

Laboratory analysis results of soil samples taken after harvest indicated that soil pH increased from 4.7 and 4.38 in the control plots to 6.12 and 5.94 at site I and II, respectively, with the application of biochar and/ or lime (Figure 3). The highest increase was recorded from combined application of Biochar + Rec lime followed by sole application of 10 t/ha biochar. In a similar study by [6] using different biochar materials and liming, soil pH, cation exchange capacity (CEC) were significantly affected by amendment type, application rate, and the interaction between them. The liming effect of biochar on acid soils was also reported by [15], who observed changes of about 1.5 pHw units after biochar amendment. This pH change was also impacted by the biochar application rate.

Biochar, which is prepared from pyrolysis of plant biomass, is normally highly alkaline material and the alkalinity varies with respect to feedstock properties used for the biochar production. The greater the alkalinity of biochar, the greater is its ability to reduce soil acidity. Thus, biochar can function as a liming agent by causing an increase in pH of soil and thus increasing availability of nutrients and improve nutrient uptake by plants for various soil types [11]. The increase in soil pH was also higher for the combined application of lime and-biochar. The $CaCO_3$ contribute to the rise in soil pH by reacting with water and CO_2, dissociate in to $2Ca^{+2}$ and $4HCO_3^-$, adsorption of $2Ca^{+2}$ on the exchange complex by replacement of H and Al ions and formation of insoluble $Al(OH)_3$ [20]. Exchangeable acidity decreased from 1.2 and 2.01 in the control plots to 0.26 and 0.43 $Cmol^+$/ kg soil in the plots that received biochar and/ or lime at site 1 and site 2, respectively.

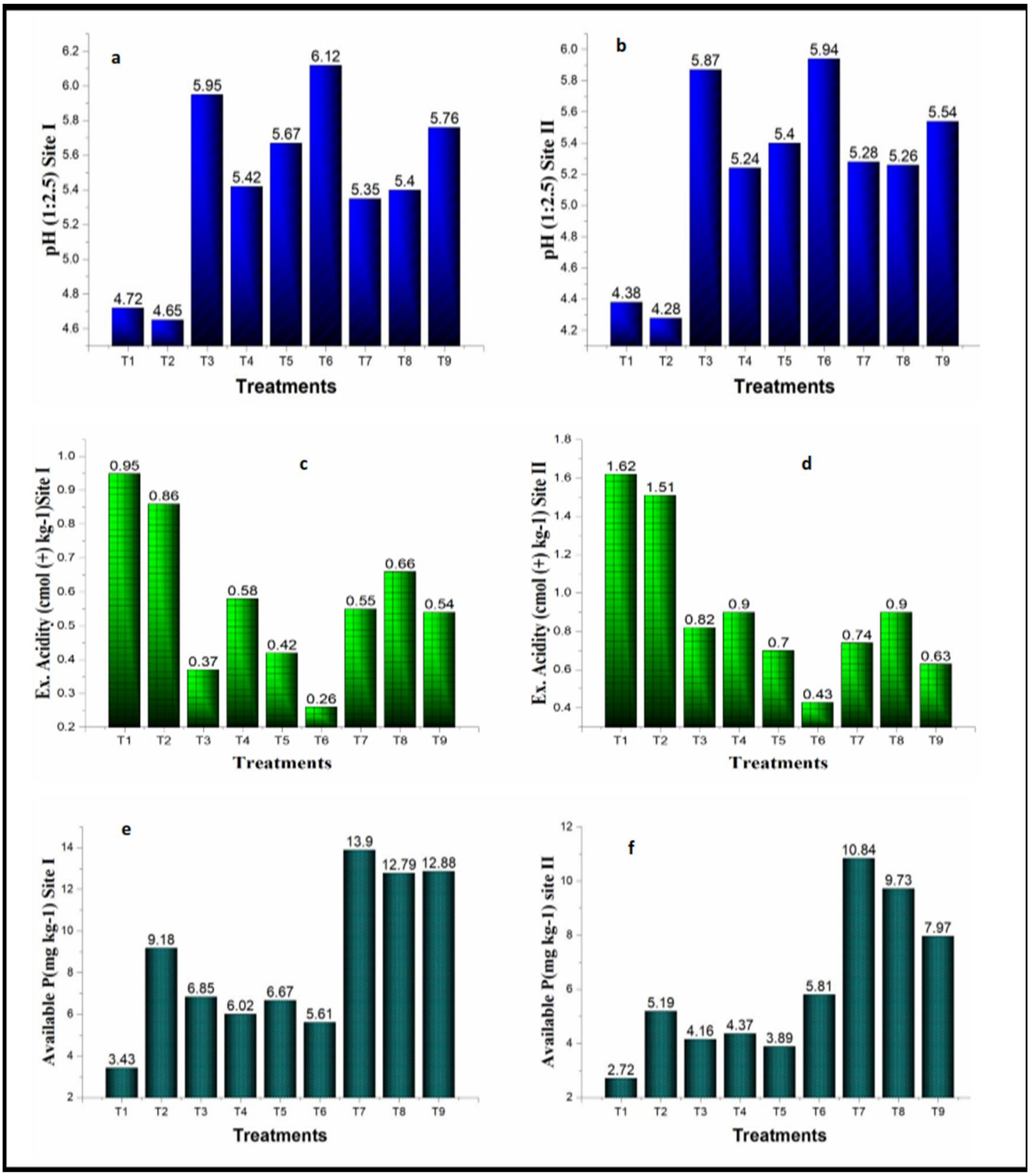

Figure 2. *Effects of biochar on soil pH, Available P and Exchangeable acidity after harvest site 1 and site 2. T1= Control, T2=Recommended NP, T3=10 t/ha Biochar, T4=5 t/ha Bio char + 50% Recommended NP rate, T5=5 t/ha Bio char + 50% Recommended lime (1.5 X EA), T6=10 t/ha Biochar + Recommended lime (1.5 X EA), T7= 10 t/ha Biochar + Recommended NP, T8=Recommended NP + Recommended L (1.5 X EA) and T9=5 t/ha Biochar + 50% Recommended NP + 50% Recommended lime, a=pH site1=b=pH site 2, c=Av. P site1, d=Av. P site 2 e=Ex. acidity site1 f= Ex. acidity site 2.*

Application of biochar and Lime, alone or in combination, enhanced available phosphorus contents of site 1and 2 (Figure 3). The highest available P contents (10.84 and 13.90 mg/kg soil) were obtained from application of Bio char (10 t/ha) + Rec. NP at site 2 and 1, respectively. The increases in available soil P could be attributed to reduced Fe and Al activity due to increase in the soil pH. In a similar study, [17] found that application of biochar with or without inorganic fertilizer increased available soil P in acidic soil, a synergistic effect between biochar and inorganic fertilizer in increasing the soil available phosphorus. Similarly, increase in soil pH could have reduced sorption of available soil phosphorus. [9] reported a greater soil available P content in biochar-amended soils compared to unamended soils and attributed the improvement to biochar's capacity to retain and exchange phosphate ions due to its positively charged surface sites.

Applications of biochar and Rec NP + Lime also increased soil organic carbon for site 1. However, the combined data analysis over locations and years does not indicate the influence of the treatment on soil organic carbon and total N.

3.2. Grain and Biomass Yield of Maize as Affected by Integrated Use of Biochar and Lime

Analysis of variance showed that there is significant different among treatment effects at site 1 and 2 during 2018 and 2019 (Table 2). The highest mean grain yield of 9499.3 kg/ha was obtained from 50% Bio char + 50% Rec. NP + 50% Rec. lime treatment at site 1 in 2018. It is statistically at par with the yields obtained from Bio char + Rec. lime (7543 kg/ha), Rec NP (7815 kg/ha), and Biochar + Rec NP (8017 kg/ha). However, from combined analysis of data over 4 locations and 2 seasons the highest mean yield (6831.8 kg/ha) was obtained from application of Bio char + Rec NP, with yield of advantage of 46% over the control and 12% over the recommended NP. Yet, it was statistically at par with Rec NP, Rec NP + Rec lime, 50% Rec NP + 50 % Bio char + 50% Rec lime. The results of the study was in agreement with [21], who reported larger yield increases when biochar was applied together with inorganic fertilizer treatments. The agronomic data is also supported by the soil test data in which application of Bio char with and without lime increase soil pH and available P and decreased exchange acidity of soils. [14] reported that biochar application improved soil quality, increased crop production and promoted plant growth.

The treatment effects on biomass yield of Maize were also significant. The combined analysis of data over locations and seasons showed that the highest biomass yield (16.4 t/ha) was obtained from application of Bio char + Rec NP, which was statistically at par with Rec NP + Rec lime and 50% Rec NP + 50 % Bio char + 50% Rec lime (Table 3).

Table 2. *Mean Grain yield (kg/ha) of Maize affected by Bio- char, NP, and lime treatments.*

Treatments	**Treatments**	**Year 1**		**Year 2**		**Mean 2018-19**
		S1	**S2**	**Site 1**	**Site 2**	
1	Control without any input	5398.7^{c}	3711.7^{e}	2563.4^{d}	3167	3710.2e
2	Rec. NP rate of the test crop	7815.7ab	5894^{bc}	7216.5^{a}	3156	6020.5bac
3	Bio char on rate based 10 t/ha	6282^{bc}	5067.3^{cd}	2703.9^{d}	4626	4669.9ed
4	50% Bio char + 50% Rec. NP rate	7203.7^{bc}	5481.3^{bcd}	5689.7^{bac}	4865	5809.9bc
5	50% Bio char +50% Rec. L(1.5 * EA)	6751^{bc}	4907d	4009.2^{bc}	4715	5095.7dc
6	Bio char + Rec. L(1.5 *EA)	7545.3^{ab}	5538^{bcd}	3793.1^{d}	3811	5171.8dc
7	Bio char + Rec. NP	8017^{ab}	6251.7^{b}	7163.6^{a}	5895	6831.8a
8	Rec. NP + Rec. L (1.5 * EA)	6962.3^{bc}	7202.3^{a}	6295.3^{ba}	5951	6602.8ba
9	50% Bio char + 50% Rec. NP + 50% Rec. L	9499.3^{a}	6096^{b}	4765.5^{bc}	5432	6448.2ba
LSD (0.05)		2070.3	900.76	1951.2	NS	1014.9
CV (%)		16.44	9.34	22.1	38.53	10.47

Table 3. Mean BY (t/ha) of Maize under Bio- char nutrient sources and limed condition.

Treatments No	Treatments description	Year 1		Year 2		Mean
		S1	S2	S1	S2	2018-19
1	Control without any input	12.4c	8.1e	9.48bc	9.98b	9.99d
2	Recom. NP rate of the test crop	17.9ab	12.8ab	9.13c	14a	13.45b
3	Bio char on rate based 10 t/ha	12.9c	9.53de	14.51a	14.73a	12.92b
4	50% Bio char + 50% Rec. NP rate	15.3abc	12.47bc	13.03ba	9.0b	12.45cb
5	50% Bio char +50% Rec. L(1.5 X EA)	15.2abc	10.03de	10.39bc	9.42b	11.27cd
6	Bio char + Rec. L (1.5 X EA)	14.1bc	10.6cd	7.69c	10.50b	10.72d
7	Bio char + Rec. NP	17.6ab	14.53a	15.65a	15.82a	16.36a
8	Rec. NP + Rec. L (1.5 X EA)	16.9abc	14.77a	14.78a	13.77a	15.05a
9	50% Bio char + 50% Rec. NP + 50% Rec. L	19.2a	13.57ab	16.23a	16.6a	15.97a
LSD (0.05)		4.46	1	3.62	2.95	1.56
CV (%)		16.4	9.77	16.97	13.49	6.87

3.3. Partial Budget Analysis

For lack of consistent data on the value of straw yield of maize, economic analysis was made based on grain yield data only. The summary of partial budget analysis showed that the highest marginal rate of return, which is 2868.60 %, was obtained from application of 50% Bio char + 50% Rec. NP + 50% Rec. lime, with net benefit of 63993.6 ETB ha^{-1} (Table 4).

Table 4. Partial budget analysis of integrated biochar, lime and organic fertilizer on maize yield.

Treatments	TY	ATY	GFB (ET Birr)	TVC (ET Birr)	NB (ET Birr)	MRR (%)
Control without any input	3710.2	3339.18	40070.16	0	40070.16	0
Rec. NP rate of the test crop	6020.5	5418.45	65021.4	2618.55	62402.85	852.86
Bio char on rate based 10 t/ha	4669.9	4202.91	50434.92	5000	45434.92	D
50% Bio char + 50% Rec. NP rate	5809.9	5228.91	62746.92	3809.28	58937.64	D
50% Bio char +50% Rec. L(1.5 * EA)	5095.7	4586.13	55033.56	4337.68	50695.88	D
Bio char + Rec. L(1.5 *EA)	5171.8	4654.62	55855.44	8675.36	47180.08	D
Bio char + Rec. NP	6831.8	6148.62	73783.44	7618.55	66164.89	86.71
Rec. NP + Rec. L(1.5 * EA)	6602.8	5942.52	71310.24	6293.91	65016.33	158.08
50% Bio char + 50% Rec. NP + 50% Rec. L	6448.2	5803.38	69640.56	5646.96	63993.6	2868.6

TY= Total yield, ATY=Adjusted Total yield, GFB =Gross Field Benefit, TVC=Total variable coast, NB=Net Benefit, MRR=Marginal Rate of Return

4. Conclusions

A field experiment was conducted in 2017/18 and 2018/19 cropping seasons with the objective of generating information on the effects of Bio-char and their interactions with lime and inorganic fertilizers on crop productivity and properties of acid soil at Kersa district, Jimma zone, South West Ethiopia. The results of the experiment showed that application of biochar alone or with inorganic fertilizer and/or lime significantly affected pH, total N, Available P, organic carbon and exchangeable acidity of soils. From the combined analysis of data over 4 locations and 2 seasons, application of Bio char + Rec NP can provide the highest grain yield of maize. However, the result was not statistically different from yields obtained by application of Rec NP alone, Rec NP + Rec lime, 50% Rec NP + 50 % Bio char + 50% Rec lime. Thus, application of anyone of the four treatments can provide statistically similar agronomic yields. The advantage of the three treatments over the Rec NP is maintenance and improvement of soil health. The results of partial budget analysis showed that highest MRR (Marginal Rate of Return) can be obtained from the combined application of 50% Bio char + 50% Rec. NP + 50% Rec. lime. Therefore, it is recommended that farmers can use 50% Bio char + 50% Rec. NP + 50% Rec. lime in order to get the highest MRR, high agronomic yields, and improved soils quality.

Abbreviations

MRR Marginal Rate of Return
SAS Statistical Analysis System

Author Contributions

Bikila Takala: Conceptualization, Formal Analysis, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing

Ewnetu Teshale: Data curation, Formal Analysis, Methodology, Resources, Software, Writing – review & editing

Adugna Bayata: Conceptualization, Data curation, Formal Analysis, Investigation, Writing – review & editing

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] Abedi, T., Alemzadeh, A., and Kazemeini, S. 2010. Effect of organic and inorganic fertilizers on grain yield and protein banding pattern of wheat," *Australian Journal of Crop Science*, vol. 4, pp. 384–389.

[2] ATA. 2014. Soil Fertility Mapping and Fertilizer blending. Agricultural Transformation Agency (ATA), Addis Ababa, Ethiopia.

[3] Blake, C. A., 1965. Methods of Soil Analysis. Part I, American Society of Agronomy. Madison, Wisconsin, USA. 1572p.

[4] Bray, R. H., Kurtz, L. T. 1945. Determination of total organic and available form of phosphorus is soils. Soil Science, 59: 39-45.

[5] Chapman, H. D. 1965. Cation-exchange capacity. In: C. A. Black et al. (eds.) Methods of soil analysis. Part 2. American Society of Agronomy, Madison, Wis.

[6] Chintala, R., J. Mollinedo, T. E. Schumacher, D. D. Malo, and J. L. Julson. 2014. Effect of biochar on chemical properties of acidic soil. *Arch. Agron. Soil Sci.* 60: 393–404.

[7] CIMMYT (International Maize and Wheat Improvement Centre). 1988. From Agronomic Data to Farmer Recommendation: An Economics Training Manual (No 27). CIMMYT. Mexico, City, Mexico.

[8] CIMMYT 1999. Maize Production Technology for the Future: Challenges and Opportunities. Proceedings of the Sixth Eastern and Southern Africa Regional Maize Conference, Ethiopia: CIMMYT (international maize and wheat improvement center), pp. 21-25.

[9] De Luca T., MacKenzie M., and Gundale J., 2009. Biochar effects on soil nutrient transformations," in *Biochar for Environmental Management: Science and Technology*, J. Lehmann and S. Joseph, Eds., pp. 251–270.

[10] Jien, S. H. and Wang, C. S., 2013. Effects of biochar on soil properties and erosion potential in a highly weathered soil. *Catena*, *110*, pp. 225-233.

[11] Laird, David A., Fleming, P., Davis, Dedrick D., Horton, R., Wang, B., and D. L., Karlen. 2010. Impact of biochar amendments on the quality of a typical Midwestern agricultural soil. Geoderma 158, 443–449.

[12] Lehmann, J. & Joseph, S. 2009. Biochar for environmental management: an introduction. In: Lehmann J and Joseph S (eds.): *Biochar for Environmental Management: Science and Technology*. Earthscan, London, pp. 1-12.

[13] Lin Q, Zhang L, Riaza M, Zhang M, Xia H, Lv B, Jiang C. 2018. Assessing the potential of biochar and aged biochar to alleviate aluminum toxicity in an acid soil for achieving cabbage productivity. Ecotoxicol Environ Saf 161: 290—295.

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

[15] Mbagwu J. S. C., Piccolo, A. 1997. Effects of humic substances from oxidized coal on soil chemical properties and maize yield. In: J. G. Drozd, S. S. Gonet, N. Senesi, J. Weber. (Eds.), *The Role of Humic Substances in the Ecosystems and in Environmental Protection: Proceedings of the 8th Meeting of the International Humic Substances Society, Polish Society of Humic Substances*, Polish Chapter of the International Humic Substances Society, Wroclaw, Poland, pp. 921–925.

[16] SAS (Statistical Analysis System) Institute. 2012. SAS for Windows software ver 9.2. SAS Institute, Inc.

[17] Sasmita K., Iswandi A, Syaiful A., Sudirman Y., and Gunawan D., 2017. Application of biochar and organic fertilizer on acid soil as growing medium for Cacao (*@eobroma cacao* L.) seedlings," *International Journal of Sciences Basic and Applied Research*, vol. 36, no. 5, pp. 261–273.

[18] Tsedeke A, Monica F, Tahirou A, Girma TK, Rodney L, Paswel M, WoinishetA 2017. Characteristics ofmaize cultivars inAfrica: How modern are they andhow many do smallholder farmers grow. Agriculture and Food Security 6: 30.

[19] Van Reeuwijk, L. P. 1992. Procedures for Soil Analysis, 3rd Ed. International Soil Reference and Information Center (ISRIC), Wageningen, the Netherlands. 34p.

[20] Weil, R. R. and Brady, N. C. 2017. The Nature and Properties of Soils, 15th ed. Person Ed Ltd. England.

[21] Zhang A, Cui L, Pan G, Li L, Hussain Q, Zhang X, Zheng J, 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.