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Reclaiming Sodium Affected Soil: The Potential of Organic Amendments

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Authors' contributions

This work was carried out in collaboration between all authors. Author DKS designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors BAO and MRA managed the analyses of the study, interpretation of results and managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

A study was conducted to evaluate the potential of organic amendments in managing sodic soils for crop production. In doing this, a pot experiment was conducted in which saw dust biochar (SDB), palm fiber biochar (PFB), poultry manure biochar (PMB) and poultry manure (PM) were applied to sodic soil sampled from an industrial area in Cape Coast, Ghana. Gypsum amendment and a control were included for the purpose of comparing results. All amendments were applied at the rate of 4.78 t ha^{-1} which was the full gypsum requirement rate for the soil. Amended soils were incubated and weekly sampled for 6-weeks (week 3 to 8) for laboratory analysis. Periodic watering was done to keep soils moisture at field capacity. From the results, organic based amendments marginally reduced soil pH and electrical conductivity (EC). Same amendments significantly (P = 0.05) increased soil Ca^{+2} and Mg^{+2}, with SDB registering the highest increase. The increases in the levels of Na^{+} and K^{+} were marginal and statistically insignificant (P = 0.05). PFB recorded the highest cation exchange capacity (CEC) at week 8 and SDB and PFB reduced soil sodicity below the minimum threshold of exchangeable sodium percentage (ESP) 15. All organic based amendments recorded marginal increase in soil organic carbon (OC) but SDB recorded the highest

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value for OC at week 8. PMB released the highest amount of available P, with peak availability observed in week 6 Insignificant (P = 0.05) increases were also observed for soil NH_4^+-N and NO_3^--N. SDB and PFB recorded 90% and 80 maize seed germination and also, 10.1 t ha^{-1} and 8.7 t ha^{-1} dry matter yields respectively. No maize seed however germinated in the control and all other amendment.

Keywords: Germination of maize seeds; saw dust biochar; palm fiber biochar; poultry manure biochar; poultry manure.

1. INTRODUCTION

From the agricultural point of view, sodic soils are soils which contain excess exchangeable sodium which adversely affects the growth of most crop plants [1]. The exchangeable sodium percentage (ESP) of such soils usually exceeds 15. Adverse effects of soil sodicity are the degradation of soil physical and nutritional properties with consequent reduction in crop growth, significantly or entirely [2-4]. Sodic soils usually exhibit electrical conductivity (EC) values below 4 dS m^{-1} and pH ranges of 8.2 to 10.5. The fundamental principle which governed the reclamation of sodic soils was the removal of part or most of the exchangeable sodium and its replacement by calcium ions and other preferred cations such as magnesium and potassium in the root zone. This involved the use of soluble calcium salts such as gypsum, calcium chloride, acids or acid forming substances, including sulphuric acid, iron sulphate, aluminium sulphate, lime-sulphur, sulphur, pyrite, and sometimes, the use of calcium salts of low solubility like ground limestone [5,6]. Organic manures have long been known to facilitate the reclamation of sodic soils [7-9]. The mechanisms involved and the precise reasons for observed responses have however remained unclear. The option of phyto-remediation has also been long exploited but found to be the slowest in terms of removing excess sodium from soil. The use of chemicals in remediation of sodic soils is not without challenges. Apart from their relative high cost, most of such chemicals are not readily available in the market. A number of them are also not user friendly. The chemical approach to reclaiming sodic soils also is largely accompanied by leaching with water, the cost of which may not be bearable in terms of reclaiming large acreages of farm land. The leachates also pose the challenge of off-site pollution [10]. Leaching may also wash away important soil-plant nutrients. The time has therefore come for researchers to come up with more sustainable and environmentally friendly methods of addressing soil sodicity. The objective of this research therefore is to evaluate the potential of biochars and poultry manure for the reclamation of sodium affected soils.

2. MATERIALS AND METHODS

The soil sample used in this experiment is the top soil (0 – 20 cm depth) of a Sodic Solonchak sampled from the land opposite Cape Coast industrial area and polluted with soap industrial effluent for 43-years. The physicochemical properties of the soil were pH (8.7), EC (3.7dS m^{-1}), Na^+ (3.1 cmol kg^{-1}), Ca^{+2} (9.3 cmol kg^{-1},) Mg^{+2} (6.5 cmol kg^{-1}), K^+ (0.8 cmol kg^{-1}), CEC (19.6 cmol kg^{-1}), ESP (18.0), OC (1.2%), NH_4^+ (26.8 mgN kg^{-1}), NO_3^- -N (18.2 mgN kg^{-1}), P (42.35 $mgkg^{-1}$), bulk density (1.4 gcm^3) and a clayey loam texture. All analysis were conducted at Soil Science Laboratory, School of Agriculture, College of Agriculture and Natural Sciences, University of Cape Coast. A pot experiment was conducted to evaluate the potential of four (4) different organic based treatments to correct the sodicity status of the soil without the conventional leaching. Applied amendments included saw dust biochar (SDB), palm fiber biochar (PFB), poultry manure biochar (PMB) and poultry manure (PM). The general properties of these materials are reported in Table 1.

All amendments were applied at the rate of 4.78 t ha^{-1} which was the full gypsum requirement rate for the soil calculated on weight basis. Results were compared to those of conventional gypsum (of same rate) and a control soil. Amendments were applied and thoroughly mixed with soil. Each amendment was replicated 5-times. The amended soils were incubated for a period of 2 weeks. After the 2 weeks period, distractive sampling was done weekly for laboratory analysis. Periodic watering of soil was done in order to keep moisture at field capacity. Soil properties monitored during the six weeks were Soil pH, electrical conductivity (EC), exchangeable sodium (Na^+), exchangeable

Table 1. Physicochemical properties of biochars and poultry manure

Properties/materials	Saw dust biochar	Palm fiber biochar	Poultry manure biochar	Poultry manure
pH (Biochar : water)	7.2	7.4	10.0	8.7
EC (dS m^{-1})	0.5	3.2	10.0	3.2
Total Organic Carbon (%)	25.3	29.9	23.5	33.1
Total Nitrogen (%)	0.5	1.	2.0	2.2
Total Phosphorus (%)	0.1	0.4	1.0	0.7
C: N	47:1	17:1	12:1	15:1
Calcium ($cmol_C$ kg^{-1})	20.5	40.8	32.4	72.5
Magnesium ($cmol_C$ kg^{-1})	1.7	23.8	69.8	29.1
Potassium ($cmol_C$ kg^{-1})	7.1	14.5	25.2	27.1
Sodium ($cmol_C$ kg^{-1})	4.0	8.0	14.8	14.6
Ex. Acidity ($cmol_C$ kg^{-1})	0.9	1.7	1.4	4.2
ECEC ($cmol_C$ kg^{-1})	34.5	67.7	143.6	144.5
ESP (%)	11.6	11.8	10.3	10.1
Fe ($mgkg^{-1}$)	6.2	12.5	5.7	6.9
Cu ($mgkg^{-1}$)	7.6	24.8	8.6	24.2
Zn ($mgkg^{-1}$)	1.6	2.62	6.0	19.4

calcium (Ca^{+2}), exchangeable magnesium (Mg^{+2}), exchangeable potassium (K^{+}), effective cations exchange capacity (ECEC), exchangeable sodium percentage (ESP), organic carbon (OC), nitrate nitrogen (NH_4^{+}-N), ammonium nitrogen (NO_3^{-} -N) and available phosphorus (P). The pH determination was done using the pH meter (soil to water ratio of 1:2.5), electrical conductivity by use of conductivity meter (sample to water ratio of 1:2). The Ca^{2+} and Mg^{2+} were determined by Atomic Absorption Spectrophotometry. Potassium and sodium were determined by the use of the flame photometer [10] and available nitrogen forms determined by Kjeldahl distillation method. For exchangeable acidity, soil was extracted with 1.0 *M* KCl (soil to extractant ratio of 1:2.5) and titrated against 0.1 *M* NaOH with phenolphthalein as indicator. Organic carbon determination was done by the potassium dichromate digestion method [11]. The digest was titrated against 0.5 M ammonium ferrous sulphate solution, using diphenylamine as indicator. The Genstart software [12] was used to perform analysis of variance (ANOVA) in order to determine the effects of the amendments on soil properties. This enabled the determination of the level of differences for measured parameters of soil samples. After the six weeks of monitoring, a sodium sensitive crop (*Zea mays L*) was planted on these soils. The local obatampa variety was used. The rate of seed germination was monitored and also, dry matter yield of above ground portion at day 45 after seed germination.

3. RESULTS AND DISCUSSION

3.1 Soil pH and Electrical Conductivity

The results of soil pH and electrical conductivity (EC) following the application of treatments and weekly sampling for six weeks are presented in Tables 2 and 3.

Table 2. Soil pH after application of amendments

Weeks/treatments	CT	GP	SDB	PFB	PMB	PM
Wk 3	8.6	8.9	7.8	8.1	7.3	8.0
Wk 4	8.7	8.9	7.9	8.1	7.1	8.3
Wk 5	8.7	8.8	7.9	7.6	7.0	8.2
Wk 6	8.6	8.7	7.9	7.6	7.1	8.3
Wk 7	8.7	8.8	7.7	7.6	7.0	8.2
Wk 8	8.7	8.8	7.7	7.6	7.1	8.1
LSD (0.05) = 0.2						
SE = 0.0365						

Table 3. Soil electrical conductivity (dsm^{-1}) after application of amendments

Weeks/treatments	CT	GP	SDB	PFB	PMB	PM
Wk 3	3.7	10.2	4.2	5.8	8.1	8.6
Wk 4	3.7	10.3	3.8	5.8	8.1	8.6
Wk 5	3.6	9.6	3.8	3.9	7.4	8.8
Wk 6	3.7	26.4	3.8	3.6	7.1	8.9
Wk 7	3.7	10.0	3.5	3.6	7.1	10.9
Wk 8	3.7	12.0	3.5	3.6	7.1	12.7
LSD (0.05) = 9.6						
SE = 1.536						

The application of gypsum resulted in a marginal increase in soil pH in week 3. The margin of increase was however not statistically significant (P = 0.05) from that of the control. This marginal increase in soil pH was constant for six weeks period. The sudden increase in soil pH after the application of gypsum could be the result of the formation of calcium salts [$CaCO_3$, and $Ca(HCO_3)_2$]. More than three-fold increase in soil EC was also observed for the same amendment through the sampling period. All the organic based amendments however resulted in significant (P = 0.05) decrease in soil pH. The average decrease in soil pH was in the order of PM<PFB<SDB<PMB. Poultry manure biochar was the least effective in reducing soil pH when compared to the other organic based amendments. Soil pH was relatively constant for SDB and PMB throughout the sampling period. In the case of PFB however, reduction in soil pH was gradual in the week 3 and 4 but the value stabilized from week 5. The general decrease in soil pH following the application of biochars and poultry manure could be attributed to the release of cations from the ash component of these biochars and also, the decomposition of poultry manure. This might have resulted in the reduction in the amount of anions on soil colloidal surface. Soil pH influences the availability of plant nutrients. The decrease in soil pH following the application of biochars and poultry manure contradicts the findings of [13-15] all of whom recorded increased pH after the application of biochar and compost. It is however worth to note that the impact of biochar/manure application on soil pH would be much influenced by the properties of the feedstock from which they are prepared. There was a general increase in soil EC following the application of all the organic based amendments. The percentages of increase were however not statistically significant (P = 0.05).

3.2 Exchangeable Ca^{2+}, Mg^{2+}, K^+ and Na^+

Values obtained for Ca^{+2}, Mg^{+2}, K^+ and Na^+ are presented in Figs. 1, 2, 3 and 4 respectively. Increased calcium levels were observed following the application of all amendments.

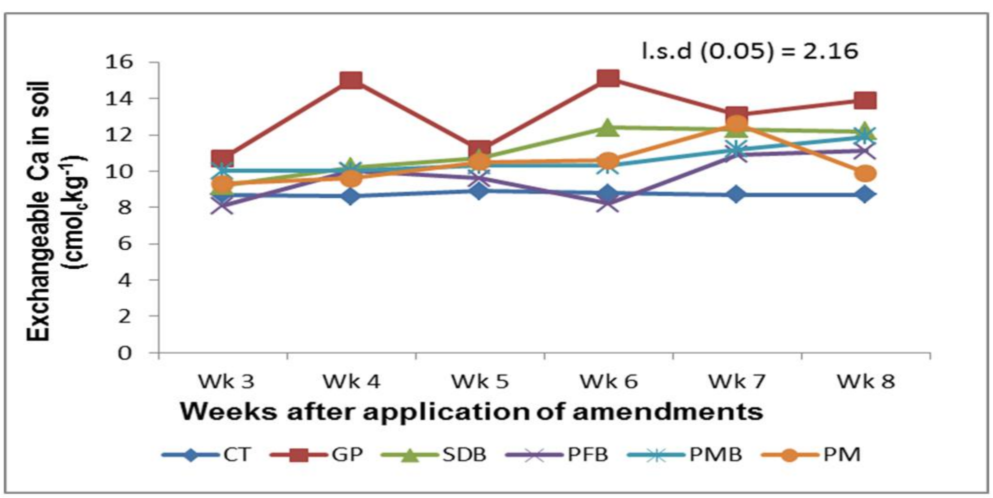

Fig. 1. Exchangeable calcium dynamics in soil after application of amendments

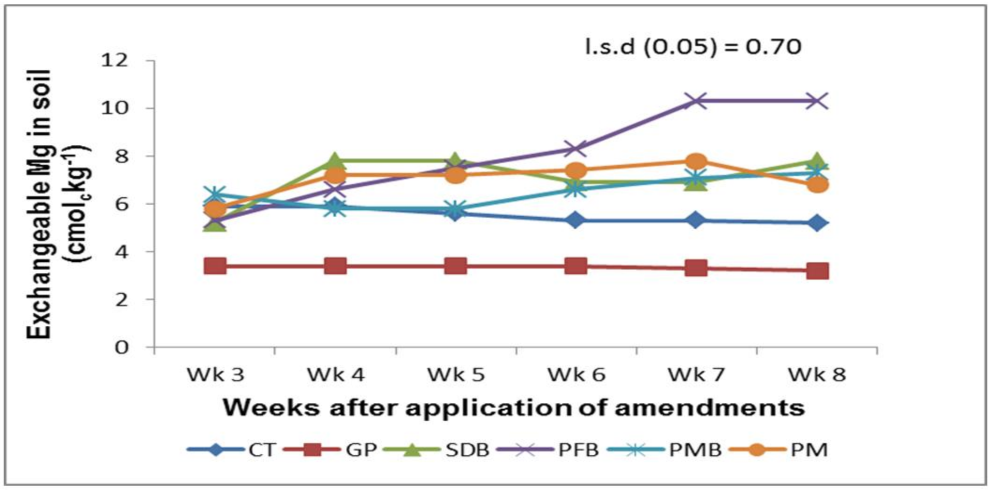

Fig. 2. Exchangeable magnesium dynamics in soil after application of amendments

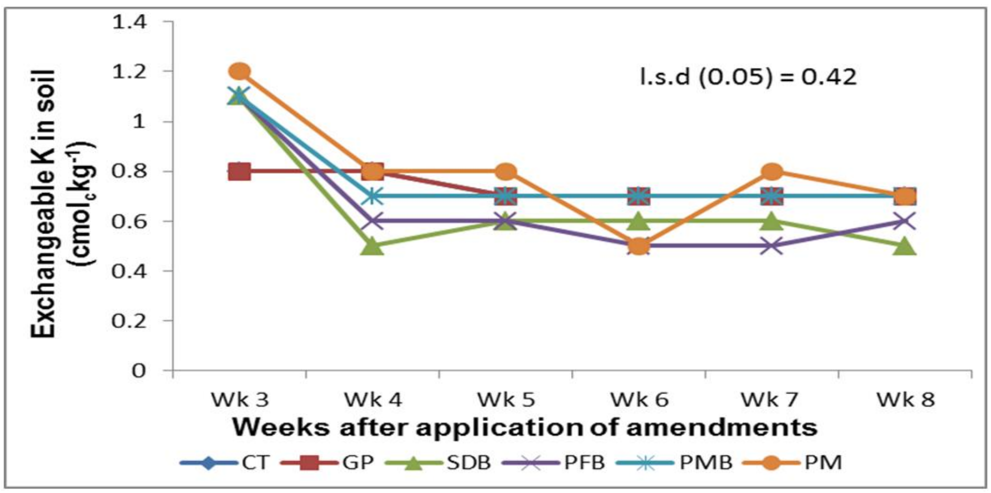

Fig. 3. Exchangeable potassium dynamics in soil after application of amendments

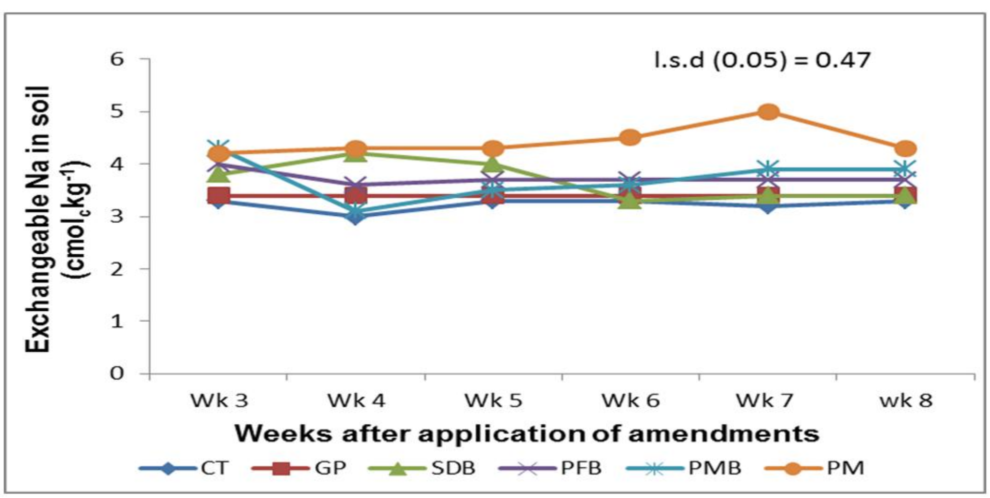

Fig. 4. Exchangeable sodium dynamics in soil after application of amendments

The differences in Ca^{+2} values were significantly (P = 0.05) different from each other. The application of gypsum recorded the highest Ca^{+2} values in week 4. Ca^{+2} release in biochar amendments increased gradually with time and obtained highest values at week 6. The peak Ca^{+2} value for poultry manure was however observed at week 5, followed by a significant decrease in availability of same in week 6. To the control, the differences in Ca^{+2} values for all amendments were statistically significant (P = 0.05). The amendments were however not significant (P = 0.05) against each other at week 6. Gypsum is a calcium concentrate and known for its ability to readily increase soil Ca^{+2} levels when applied. The gradual release of Ca^{+2} by the biochars and the poultry manure to almost the same level of gypsum provided the basis that these organic amendments could replace gypsum in terms of calcium supply in soil. Significant (P = 0.05) decrease in soil Mg^{+2} was observed after the application of Gypsum. The values for same however increased gradually in biochars and manure amendments over time, with highest values recorded in week 6. At week 6, Mg^{+2} release was highest for PFB, followed by saw dust biochar.

Organic based amendments increased soil K^{+} values by an average of 0.33 cmol kg^{-1} in week 3. This increase was however not statistically significant (P = 0.05) from that of the control. Soil K^{+} levels however declined from week 4 through to week 8. This could be attributed to microbial immobilization for decomposition of applied organic matter.

Marginal increase in soil Na^{+} was observed following the application of all amendments. The margin of increment was also not significant (P = 0.05) from the control. Calcium plays a crucial role in soil nutrition and plant root development. Magnesium is also the central element of chlorophyll. Potassium plays crucial role in plant reproduction and considered second to nitrogen. Sodium, though required in relatively small quantities, also plays important role in plant growth. [16] observed increased soil Ca^{2+} and Mg^{2+} availability when biochar was applied at 20 t ha^{-1} to a Colombian savanna oxisol. In an Iowa study, [17] found a significant increase in Ca^{2+} levels when biochar was applied to soil at 20 g Kg^{-1} soil. [13-15] also observed significantly increase in the levels of Ca^{+2}, Mg^{2+}, K^{+} and Na^{+} following the application of biochar and compost. Per these research findings, therefore, biochar could be a significant source of these cations [4] and could potentially help in sodic soil remediation.

3.3 Cation Exchange Capacity and Exchangeable Sodium Percentage

Cation exchange capacity (CEC) represents the total amount of positively charged ions that a soil can hold [14]. A higher CEC indicates the capacity of the soil to adsorb and hold nutrients and therefore, higher nutrient availability in soil. Soil analysis showed that biochars and poultry manure amendments significantly (P = 0.05) increased soil CEC compared to the control and gypsum (Table 4).

Organic amendments exhibited gradual increase in soil CEC over time, with PFB recording the highest CEC at week 6. The order of increase in CEC at week 6 was CT<GP<PM<PMB<SDB<PFB. All biochar amendments improved soil CEC better that non-biochar amendments. Literature explains that biochar is a variably charged organic material with high surface area and highly porous. It thus has the potential to increase soil CEC, surface sorption capacity and base saturation when added to soil [15,18,19]. Increased soil CEC after biochars application was therefore due to increase in charge density per unit surface of organic matter which equates to a greater

Table 4. Cation exchange capacity of soil ($cmol_c kg^{-1}$) after the application of amendments

Weeks/treatments	CT	GP	SDB	PFB	PMB	PM
Wk 3	18.5	18.2	19.2	18.6	22.0	20.7
Wk 4	18.2	21.8	22.4	20.6	19.4	21.9
Wk 5	18.5	18.7	22.4	21.4	20.4	22.8
Wk 6	18.1	22.4	23.4	22.7	21.1	23.0
Wk 7	18.0	20.7	22.8	25.4	22.9	26.4
Wk 8	18.0	21.4	24.0	25.6	23.8	21.7
LSD (0.05) = 2.2						
SE = 0.553						

degree of oxidation or increases in surface charge area for cation adsorption or a combination of the two [20].

From Table 5, the effectiveness of amendments in reducing soil sodicity was in the order of PMB (9.3%) < GP (12.6%) < SDB (21.9%) = PFB (21.9%). SDB and PFB reduced soil sodicity below the minimum threshold of ESP 15. PMB however could not. It is worth stating that SDB and PFB exhibited relatively high Ca^{+2} and Mg^{+2} values at week 6. The sum of the divalent cations to the total cation concentration of those amendments had therefore increased, leading to the reduction in the percentage soil colloidal surface occupied by Na^{+}. Besides, the amount of lignin contained in biochar could influence its rate of decomposition and release of plant nutrients in the soil medium. Significant reduction in the ESP of soils amended with biochar and compost were reported by [21-23]. Those experiments were however accompanied by leaching after the amendments were applied. Without leaching; gypsum applied at the rate of full gypsum requirement (4.78 t ha^{-1}) was not able to reduce soil sodicity appreciably. The addition of gypsum introduced more Ca^{+2} into the soil regime. This increased the percentage of soil colloidal surface occupied by divalent cations. This phenomenon resulted in a marginal reduction in soil ESP. This margin of ESP decrease however could not bring the soil below ESP threshold. Chances are that, the application of gypsum above the rate of gypsum requirement could reduce ESP below threshold without leaching. The performance of PMB was similar to that of gypsum but the application of PM rather increased soil sodicity by 9.3%. This could be attributed to the ease of decomposition of PM to release more Na^{+} when compared to biochar. A peculiar feature of this experiment is that the soils were not leached after amendments were applied. Rather, soils were sampled and extracted. The study showed that biochars could perform similar or even better than gypsum which was most popular amendment used for reclaiming sodic soil. The differences in the performance of the biochars could also be influenced by the ease of decomposition and release of plant nutrients.

3.4 Soil Organic Carbon and Available Phosphorus after the Application of Amendments

Results obtained for soil organic carbon (OC) after the application of amendments are reported in Table 6.

All organic based amendments resulted in an increased soil OC. Most of the OC increases were however not statistically significant (P = 0.05) from each other. Saw dust biochar (SDB) recorded the highest value for OC at week 6; an

Table 5. Exchangeable sodium percentage (%) after the application of amendments

Weeks/treatments	CT	GP	SDB	PFB	PMB	PM
Wk 3	18.0	18.6	19.4	21.9	19.7	20.3
Wk 4	17.0	15.8	18.4	17.4	16.2	19.8
Wk 5	18.0	18.5	18.0	17.1	17.2	19.8
Wk 6	18.0	16.0	14.4	16.5	17.2	19.6
Wk 7	18.2	17.0	14.9	14.5	16.5	19.1
Wk 8	18.3	16.0	14.3	14.3	16.3	20.0
LSD (0.05) = 2.5						
SE = 0.522						

Table 6. Soil organic carbon (%) after application of amendments

Weeks/treatments	CT	GP	SDB	PFB	PMB	PM
Wk 3	0.8	0.9	0.8	0.9	0.9	1.0
Wk 4	0.8	0.9	0.9	0.9	0.8	1.0
Wk 5	0.8	0.9	0.9	0.9	0.8	0.9
Wk 6	0.8	0.8	0.8	0.8	0.7	1.0
Wk 7	0.9	0.9	0.8	0.9	1.0	1.0
Wk 8	0.7	0.9	1.1	0.9	0.9	1.0
LSD (0.05) = 0.4						
SE = 0.0603						

increase which was statistically significant (P = 0.05) over the control. The relative OC increases from application of the biochars and poultry manure could be from the presence of high amount of OC in feed stocks. The highest value of OC from a biochar amended soil indicated the recalcitrance and high stability of C-organic in biochar. High OC in soils amended with biochar were also reported by [15,19,24]. Increased OC level of soil could be very valuable in restoring degraded soil physical properties of agricultural soils. The impacts of amendments on soil available phosphorus (P) are presented in Table 7.

SDB, PFB and PM all recorded marginal but insignificant (P = 0.05) increases in soil available P over the control soil. PMB however recorded significant (P = 0.05) increase in available P over the control throughout the six weeks. Peak P availability was observed in week 4. It is worth to note that, PFB exhibited the highest percent of total P when the amendments were characterized (Table 4). The application of gypsum rather resulted in the depletion of soil available P. This could be attributed to fixation following the introduction of calcium divalent cations into the soil medium [25,26].

3.5 Ammonium and Nitrate Nitrogen after the Application of Amendments

Figs. 5 and 6 represent values obtained for ammonium nitrogen (NH_4^+-N) and nitrate nitrogen (NO_3^--N).

Increases observed in soil $NH4^+$-N levels were not significantly (P = 0.05) different from the control. The availability of NH_4^+-N also decreased with the passage of time. More of $NH4^+$-N was observed in soil than NO_3^--N. In a similar trial, [27] showed that biochar had high adsorption for NH_4^+-N and virtually none for NO_3^--N. There are contradictory reports regarding the availability of nitrogen when biochar is applied. Some researchers reported N-increase, some, N-decrease and others, no effect [28-31]. To explain these dynamics, however, the role of factors such as composition of feedstock, pyrolytic temperature, application rates, resident time in soil, soil properties among other things should be well understood.

Table 7. Available phosphorus (mgkg^{-1}) after application of amendments

Weeks/treatments	CT	GP	SDB	PFB	PMB	PM
Wk 3	29.6	22.6	27.4	25.6	38.9	31.2
Wk 4	30.1	22.4	26.7	24.9	36.4	30.5
Wk 5	30.9	22.4	26.8	24.9	38.2	30.5
Wk 6	28.4	20.7	27.5	24.9	43.6	24.4
Wk 7	23.8	19.2	27.4	27.2	37.1	27.1
Wk 8	28.9	19.4	29.5	16.7	39.4	24.6
LSD (0.05) = 11.1						
SE = 4.436						

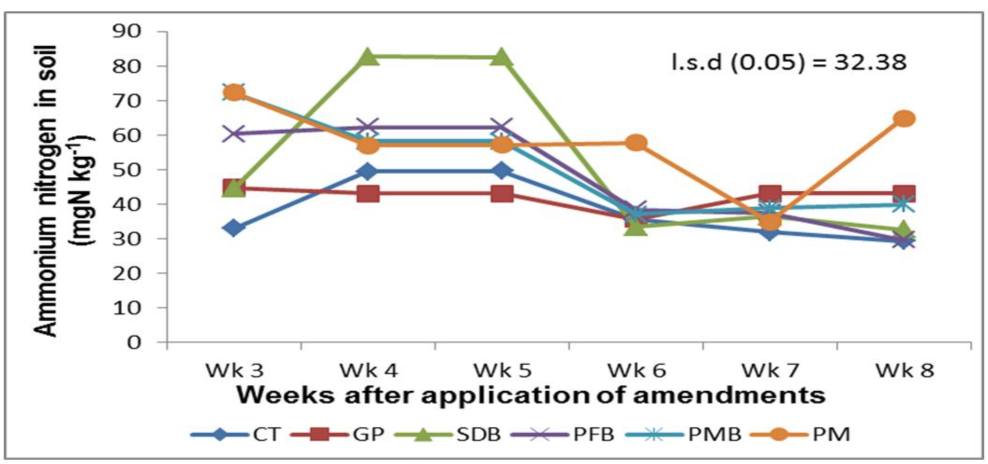

Fig. 5. Ammonium Nitrogen ($NH4^+$-N) after application of amendments

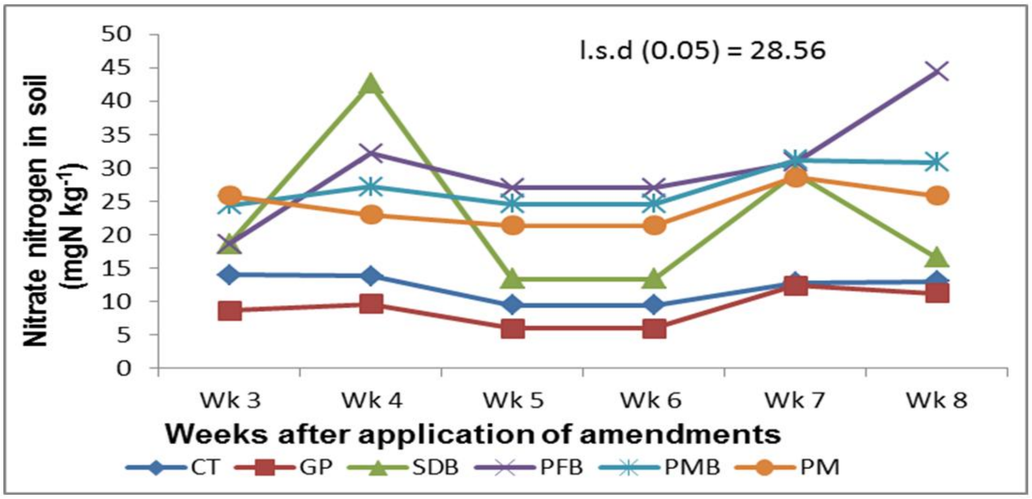

Fig. 6. Nitrate Nitrogen (NO_3^--N) after application of amendments

3.6 Seed Germination Test

The maize seed germination test after week 6 soil sampling showed a 90% maize seed germination in soils amended with SDB, followed by 80% seed germination in PFB amended soils. No maize seed germinated in the control soil and also, all other amendments where ESP levels were still high. The SDB amended soils yielded 10.1 t ha^{-1} dry matter as against 8.7 t ha^{-1} for PFB.

4. CONCLUSION

The purpose of this study was to use locally available organic amendments to manage a sodic soil for crop production (without leaching). Saw dust biochar (SDB), palm fiber biochar (PFB), poultry manure biochar (PMB) and poultry manure (PM) were the organic amendments applied at gypsum requirement rate of 4.78 t ha^{-1}. The effectiveness of amendments in reducing soil sodicity was in the order of PMB (9.3%) < GP (12.6%) < SDB (21.9) = PFB (21.9%). SDB and PFB reduced soil sodicity below the minimum threshold of ESP 15. All organic based amendments resulted in marginal increase in soil OC though such increases were not statistically significant (P = 0.05). Saw dust biochar (SDB) recorded the highest value for OC at week 6. PMB maintained significant (P = 0.05) increase in available P over the control throughout the six weeks, with peak availability observed in week 4. General increase in the levels of soil NH_4^+-N was observed following the application of amendments. High levels of $NH4^+$-N were also observed in soil relative to those of NO_3^--N. There was 90% maize seed germination in soils treated with SDB, and 80% seed germination for PFB. No maize seed germinated in the control and all other amendments. SDB amended soils yielded 10.1 t ha^{-1} dry matter as against 8.7 t ha^{-1} for PFB. Cost benefit is however necessary to consolidate the usefulness of biochar in managing sodic soils.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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