Potential of biochar and organic amendments for reclamation of coastal acidic-salt affected soil

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Abstract

Salinity and acidity have affected several hundred million hectares of land throughout the globe which poses a major threat to global food security and biodiversity. Application of organic amendments for salt-affected soils has been identified as one of the most effective ways to mitigate salinity-induced problems and considered as a green technique offering twin benefits of waste load reduction and land reclamation. However, studies on reclaiming acidic-salt affected soils are limited. Therefore, this study aimed to determine the reclamation potential of biochars and organic amendments involving *Gliricidia sepium* biochar produced at 300 °C, 500 °C, and 700 °C, green waste compost, and municipal sewage sludge at three different amendment ratios, 1.0%, 2.5% and 5.0%. The incubation experiment was conducted for a 4-month period with different amendment ratios applied to the coastal acidic-salt affected soil. Subsamples were extracted from incubation pots after 1 and 4 months and analyzed for soil chemical parameters (pH, EC, NO_3^-, PO_4^{3-}, total organic carbon, cation exchange capacity, sodium adsorption ratio, exchangeable sodium percentage) and microbial enzyme activity (catalase activity, and acid- and alkaline phosphatase activity). All organic amendments demonstrated enhancement of the soil properties in a significant manner. However, increasing incubation time and amendment ratio increase the changes of soil parameters by a great percentage. Therefore, the maximum amendment ratio of 5.0% and 4 months of incubation period rendered a significant improvement in the reclamation of acidic-salt affected soil. However, the biochar produced at 500 °C contributed the maximum towards the improved physicochemical and biochemical profile of acidic-salt affected soil, making it the most promising organic amendment for the reclamation of acidic-salt affected soil. The overall reclamation efficiency of organic amendments registered the following order of variation: 700 BC < Sludge < 300 BC < Compost < 500 BC.

Keywords Salinity · Soil acidity · Compost · Biosolids · Soil amendment

1 Introduction

Soil salinization has affected approximately 1128 million hectares of the land area throughout the world, making it one of the fundamental threats to global food security (Wicke et al. 2011). It is caused by various environmental and anthropogenic factors such as weathering of salt-containing rocks, increased rate of evaporation of surface water, low rate of precipitation, underdeveloped agricultural practices, fertilizer application, and saltwater irrigation (Shrivastava and Kumar 2015). Due to global climatic changes and increasing anthropogenic activities, soil salinization has become a serious and perpetuating process threatening precious land resources. The total area of salt-affected soil is increasing annually at a rate of 10%, and more than 50% of land on the Earth would be affected by the year 2050

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(Jamil et al. 2011; Shrivastava and Kumar 2015). Major regions of the world affected by salinization include United States, China, India, Pakistan, Sudan, Argentina, and several countries in western and central Asia (Ghassemi et al. 1995; Daliakopoulos et al. 2016).

Salt-affected soils are characterized by the presence of sodium, calcium, magnesium, chlorides, sulfates, carbonates, and bicarbonates at elevated concentrations (Manchanda and Garg 2008). However, based on sodium ion and salt concentration, salt-affected soils are categorized into saline, sodic, and saline–sodic soil. Approximately, 40% of salt-affected soils all over the world are saline soils, and the other 60% comprise sodic soils (Brady and Weil 2002; Qadir et al. 2006). In general, salt-affected soils are alkaline, however, the acidity may increase when the sulfidic environment reigns in soils as encountered in coastal acid sulfate soils. Oxidation of sulfidic sediments via drainage creates rapid acidification with an increase in salinity due to the enhanced mobilization of trace metals and the release of other cations such as K^+, Na^+, and Mg^{2+}, leading to the formation of acidic-salt affected soil (Huang et al. 2014).

An increase in acidity and salinity in soil generates negative impacts on socio-economical, environmental, and human health-related aspects. A vast area of agricultural land throughout the world has been affected by the soil acidity and salinity, and it is estimated that approximately 33% of irrigated lands and 20% of total cultivated lands have been affected (Shrivastava and Kumar 2015). Therefore, the reclamation of acidic-salt affected lands and the prevention of further degradation are vital needs of the present time to ensure global food security and conservation of biodiversity.

Mitigation techniques for soil salinization and acid sulfate soils include the introduction of salt-tolerant crop species, removal of salt from the root zone by leaching, implementation of proper land management and irrigation techniques, and adoption of soil amendments to ameliorate the soil acidity and salinity. Cultivation of salt-tolerant crop varieties is one of the best strategies to use salt-affected lands effectively for crop production. However, breeding of novel salt-tolerant crop varieties is a long-term process, and the use of transgenic crops with salt tolerability is not accepted by many nations, considering the risks associated with them (Gunarathne et al. 2019). Furthermore, the leaching of soluble salts with excessive irrigation also is effective for mitigating salinity (Corwin et al. 2007). However, all of these techniques require ample availability of quality water resources, which is often limited in high salinity-affected areas, and it creates a practical constraint for their implementation (Shrivastava and Kumar 2015). Therefore, the application of soil amendments has been considered as one of the cost-effective and easy-to-use techniques for mitigation of soil acidity and salinity.

Soil amendments that have been studied for the reclamation of salt-affected and acid sulfate soils can be divided into two main categories, namely, inorganic and organic amendments. Gypsum, calcium chloride, and sulfuric acid are the widely applied inorganic soil amendment agents having proven reclamation potential for salt-affected soils; whereas, alkaline amendments are used for acid sulfate soils (Amezketa et al. 2005; Ahmad et al. 2013; Gharaibeh et al. 2009). Mineral amendments are considerably expensive and can pose negative impacts on native soil microflora which limit their use as an economically and environmentally feasible method. On the other hand, the application of organic amendments can both ameliorate the salt-affected soils and increase soil fertility, supplying macro- and micro-nutrients for plants.

Moreover, organic amendments like biochar, compost, and sewage sludge are generally derived from economically viable sources of secondary waste materials; thus, their application for reclamation purposes has been considered as a green technique. Therefore, many of the recent studies have been focused on evaluating the potential of organic amendments for reclamation of salt-affected soils (Huang et al. 2019; Yupeng et al. 2018; Zhang et al. 2015). Furthermore, since salinization affects the soil carbon storage, over a long period, it causes a significant reduction in soil organic carbon (Wong et al. 2010). Therefore, the application of organic amendments such as biochar into the salt-affected soil can restore the soil organic carbon store making the soil suitable for the growth of plants and soil microorganisms. However, most researches have focused on saline or saline–sodic soils or acid sulfate soils, and the attention to reclaim acidic-salt affected soil which may help to mitigate the likelihood of developing acid sulfate soils. Therefore, the objectives of this study are to determine the effects of three different organic amendments at different application ratios on chemical and biochemical profiles of the acidic-salt affected soil and to ascertain the best organic amendment material and amendment ratio for improving the quality of the acidic-salt affected soils.

2 Materials and methods

2.1 Soil sampling and material preparation

The acidic-salt affected soil was collected from Kokkuvil located at a distance of 1–2 km from Batticaloa lagoon (latitude 7°44′41.5″ N and longitude 81°39′17.2″ E) in Chenkaladi divisional secretariat, Sri Lanka. Soil samples were taken from five random auger points up to a depth of 30 cm and mixed thoroughly to make a composite sample. Approximately, 500 g of subsample was separated from the composite soil sample, and an aliquot of the air-dried 2-mm sieved subsample was taken to carry out further experiments.

Three types of wood chip biochar produced from *Gliricidia sepium* at 300 °C, 500 °C, and 700 °C, green waste compost, and municipal sewage sludge were used as organic amendments for this study. The wood chip biochar was produced via pyrolysis of oven-dried woody biomass of *G. sepium* using a muffle furnace (P300, Nabertherm, Germany) with a temperature ramping of 7 °C per minute and heating time of 3 h. Green waste compost was collected from the municipal council affiliated compost producer in Gampola, Sri Lanka. The green waste compost consisted of residual landscape green materials. Municipal sewage sludge was collected from the Hanthana wastewater treatment plant, which is affiliated to the water supply and drainage board of Sri Lanka.

2.2 Characterization of soil and organic amendments

All the chemicals used for this study were analytical grade and were purchased from either Fluka (Switzerland) or Sigma (USA).

2.2.1 Chemical properties

2.2.1.1 Electrical conductivity and pH Electrical conductivity (EC) and pH measurements were made on saturated paste extracts using conductivity meter (Orion 5 Star, Thermo Scientific) and pH meter (702 SM Titrino, Metrohm, Swiss). 1-g sample of either soil or organic amendment was shaken with 10 mL of de-ionized water for 4 h at 100 rpm, and the pH and EC of the resulted suspension were measured.

2.2.1.2 Nutrient status The available nitrate and phosphate concentrations, and total organic carbon content of soil and organic amendments were determined following the standard colorimetric methods mentioned in Anderson and Ingram (1993). Available nitrate concentration was measured using the K_2SO_4 extraction method, available phosphate concentration was evaluated using the Olsen method, and modified Walkley–Black method was employed to determine the total organic carbon content. The absorbance of color-developed supernatant solutions for nitrate and total organic carbon was measured using a UV–Visible spectrophotometer (UV-160A, Shimadzu) at the respective wavelengths of 410 nm and 600 nm. Similarly, for phosphate, the absorbance of the color-developed solution was measured at 880 nm wavelength using a UV–Visible spectrophotometer (UV-5420, Shimadzu).

2.2.1.3 Cation exchange capacity The cation exchange capacity (CEC) was determined using the Bower method by NH_4^+ saturation using 1 M ammonium acetate solution at pH 7.0 (Anderson and Ingram 1993). After the extraction step, the solution was shaken at 100 rpm for 15 min and centrifuged for 10 min at 2000 rpm and filtered. The filtrate was analyzed for exchangeable cations: Na^+, K^+, Ca^{2+}, and Mg^{2+} by an atomic absorption spectrophotometer (AAS-Model GBC Shimadzu AA/7000933 AA). The CEC for acidic-salt affected soil and organic amendments was calculated using resulted concentrations of exchangeable metals.

2.2.1.4 Sodium adsorption ratio Sodium adsorption ratio (SAR) was determined using Eq. 1, where Na^+, Ca^{2+}, and Mg^{2+} are respective soluble cation concentrations given in cmol kg^{-1}.

$$SAR = \frac{Na^+}{\sqrt{\frac{(Ca^{2+}+Mg^{2+})}{2}}} \quad (1)$$

2.2.1.5 Exchangeable sodium percentage The concentration of exchangeable cation was measured as the concentration difference between the extractable and soluble cations (Chaganti and Crohn 2015). Equation 2 was used to calculate exchangeable sodium percentage (ESP).

$$\mathrm{ESP} = \frac{(Na^+)}{\mathrm{CEC}} \quad (2)$$

2.2.2 Soil biochemical properties

2.2.2.1 Acid and alkaline phosphatase activity Four milliliters of modified universal buffer (MUB) adjusted to pH 6.5 (for acid phosphatase) or pH 11 (for alkaline phosphatase), 0.25 mL of toluene and 1 mL of p-nitrophenyl phosphate (PNP) solution prepared in the same buffer solutions were added for 1.0 g of acidic-salt affected soil and swirled for a few seconds to mix the solution. The solution was incubated at 37 °C, and after 1 h, 1 mL of 0.5 M calcium chloride and 4 mL of 0.5 M sodium hydroxide were added. The filtrate was measured for the absorbance of the yellow-colored complex at 325 nm by UV spectrometer (UV-160A, Shimadzu, Japan), and the results were expressed as µg (p-nitrophenol) g^{-1} h^{-1}.

2.2.2.2 Catalase activity Catalase activity was assessed based on the rate of recovery of hydrogen peroxide. Forty milliliters of distilled water and 5 mL 0.3% H_2O_2 were added for the 2.0 g of air-dried acidic-salt affected soil, and the mixture was shaken using a mechanical shaker (B603, Eyela, Japan) for 20 min at 150 rpm followed by centrifugation for 10 min at 2500 rpm. The filtrate was titrated with

0.05 mol dm^{-3} $KMnO_4$ solution in the presence of sulfuric acid (5 mL of 1.5 mol dm^{-3} H_2SO_4), and the results were expressed as mL (0.05 mol L^{-1} $KMnO_4$) g^{-1} h^{-1} (Jin et al. 2009).

Furthermore, bulk density, water holding capacity, sulfate content, and metal content were determined only for acidic-salt affected soil using the standard methods mentioned in Anderson and Ingram (1993).

2.3 Soil treatments and incubation experiment

The acidic-salt affected soil samples (150 g) were incubated in separate plastic pots with biochar prepared at 300 °C, 500 °C, and 700 °C, green waste compost, and municipal sewage sludge with three different mass ratios, 1%, 2.5% and 5% along with respective controls. Three replicates were maintained for each treatment. The organic amendment-treated soils along with the control were subjected to laboratory incubation for 120 days at room temperature (26 ± 1 °C). Throughout the incubation period, the water content in all pots was maintained at field capacity.

2.4 Biochemical analysis of amended soil after incubation

After 1 month of incubation period, 50 g of sub-sample was taken from each treatment pot, and the incubation is continued for the rest of the sample maintaining the same soil water status. Soil subsamples were tested for pH, electrical conductivity (EC), soil available nitrate and phosphate, total organic carbon, cation exchange capacity (CEC), acid and alkaline phosphatase activity, and catalase activity. After 4 months, the second sub-sample was taken from each treatment pot and tested again for the above parameters.

2.5 Statistical analysis

The results of all parameters obtained for all treatments under 1-month and 4-month incubations were subjected to statistical analyses separately performing one-way ANOVA after conducting the Anderson–Darling test for normality of data distribution. Pairwise comparisons were made among the treatments using Tukey's multiple comparison test at 95% confidence levels. All statistical tests were carried out using Minitab® statistical software (Ver. 16.1.0).

3 Results and discussions

The chemical and biochemical characteristics and elemental composition of the topsoil (0–20 cm depth) of the Kokkuvil coastal area are stated in Tables 1 and 2. The soil is exceptionally acidic with a pH of 4.04 ± 0.02. The cation exchange

Table 1 Chemical and biochemical properties of acidic-salt affected soil

Saline-acidic soil													
Bulk density	Water holding capacity	SO_4^{2-}	EC (1:10)	pH (1:10)	NO_3^-	PO_4^{3-}	CEC	SAR	ESP	TOC	Catalase activity	Phosphatase activity (acidic)	Phosphatase activity (alkali)
g cm^{-3}	%	mg kg^{-1}	dS cm^{-3}		mg kg^{-1}	mg kg^{-1}	cmol kg^{-1}		%	%	mL (0.05 mol L^{-1} $KMnO_4$) g^{-1} h^{-1}	µg (p-nitro-phenol) g^{-1} h^{-1}	µg (p-nitro-phenol) g^{-1} h^{-1}
1.20 (0.21)	35.0 (1.6)	567.5 (11.8)	4.91 (0.03)	4.04 (0.02)	0.22 (0.06)	5.44 (0.08)	32.68 (1.02)	10.66 (1.05)	67.62 (2.59)	4.60 (0.06)	6.86 (0.11)	158.24 (7.71)	60.95 (5.82)

The value given for each parameter is the mean of three determinations, and the standard deviation (SD) for each value is mentioned in parenthesis

EC electrical conductivity, *CEC* cation exchange capacity, *SAR* sodium adsorption ratio, *ESP* exchangeable sodium percentage, *TOC* total organic carbon

Table 2 Elemental composition of acidic-salt affected soil

Elemental composition	Na^{+} mg kg^{-1}	K^{+}	Ca^{2+}	Mg^{2+}	Cu^{2+}	Fe^{2+}
	5811.23 (4.86)	2744.64 (10.01)	1550.81 (10.05)	1030.87 (9.35)	0.792 (0.009)	304.62 (1.03)

The value given for each parameter is the mean of three determinations, and the standard deviation (SD) for each value is mentioned in parenthesis

capacity of the examined soil remains within 32.68 ± 1.02 cmol kg^{-1}, and the total organic carbon percentage is relatively low (4.60 ± 0.06). Moreover, the soil is deficient in the nitrate and phosphate concentrations (0.22 ± 0.06 and 5.44 ± 0.08 mg kg^{-1}), respectively but considerably rich in iron concentration (304.62 mg kg^{-1}). The soil in Kolluvil coastal plain area furnishes poor fertility features owing to a suite of unfavorable factors such as acidic pH arising possibly from the oxidation of sulfidic environment, low cation exchange capacity, depleted nitrate and phosphate concentrations, excess amount of Fe^{2+} and diminutive soil organic carbon content. Such characteristics of highly acidic nature, nutrient deficiency, and iron and SO_4^{3-} richness are generally exhibited by acid sulfate soils found in many coastal areas throughout the world (Fanning et al. 2002; Burton et al. 2008). Although the occurrence of acidic-salt affected soils is rare throughout the world, many studies carried out for acidic-salt affected soils in Kerala, South India, found high acidity associated with it (Swarajyalakshmi et al. 2003; Nayak and Rao 1980; Siddaramappa and Sethunathan 1975). This acidic-salt affected soil, which is locally known as ‘Pokkali’ in South India, shows characteristics identical to the acidic-salt affected soil tested in the present study. Moreover, both soils have characteristically low pH values that vary from pH 4.0 to 4.2, low concentrations of nitrate, elevated concentrations of sulfates, and approximately similar organic matter contents (Nayak and Rao 1980; Venkateswarlu et al. 1977; Swarajyalakshmi et al. 2003).

Results of the chemical and biochemical analyses of the three types of biochar, composts, and sludge are shown in Table 3. The biochar produced at 300 °C showed the lowest EC value, pH, and available PO_4^{3-} compared with the other two types of biochar (i.e., 500 BG and 700 BC). However, 300 BC had the highest TOC, catalase, and acid- and alkaline phosphatase activities as compared to the other biochars, but the lowest nitrate, SAR and ESP among all the amendments. In contrast, the 700 BC showed the lowest TOC, catalase, acid- and alkaline phosphatase activities among the organic amendments examined. Further, the chemical and biochemical parameters including, EC, ESP, TOC, catalase, acid- and alkaline phosphatase activity of 500 BC showed intermediate characteristics. It had the highest pH and phosphate among all the organic amendments and the maximum SAR and nitrate content among all types of biochar. Therefore, the pH value of biochar tended to change slightly, from acidic to alkaline, with an increment of production temperature from 300 °C to 700 °C, while EC values showed a gradually increasing trend. However, acid phosphatase, alkaline phosphatase, and catalase enzyme activities decreased drastically with the increase in production temperature.

The compost recorded the highest contents of TOC and nitrate as compared with the other organic amendments. Moreover, the compost had a slightly alkaline pH value. The sludge reported the highest SAR, ESP, acid phosphatase, and alkaline phosphatase activity as compared with all amendments. Furthermore, the sludge showed the lowest EC, pH, and phosphate levels among all amendments. Therefore, all organic amendments considered in this study presented different chemical and biochemical characteristics that might influence for different degrees of reclamation of acidic-salt affected soil as a result of the amelioration of adverse attributes.

3.1 Changes in soil chemical properties

Figure 1 indicates the electrical conductivity (EC) of acidic-salt affected soil treated with different organic amendments at three different ratios, after 1 month and 4 months of incubation periods. After the 1 month of the incubation period, the highest value for EC was reported from the treatment with 2.5% of the sludge, and it was 5.29 ± 0.45 mS cm^{-1}. Although, all the treatment with 700 BC, compost and sludge with any of the amendment ratio after the 1 month of incubation period showed significantly higher ($p < 0.050$) EC value than the treatments with 300 BC, 500 BC, and the control. However, after 4 months of incubation period, the control set reported the highest EC value (4.93 ± 0.14 mS cm^{-1}); while, all the treatments with organic amendments showed significant reduction ($p < 0.050$) compared to the control except 2.5% and 5.0% amendment ratios of 700 BC and 1.0% amendment ratio of compost. Moreover, treatment with sludge at the highest amendment ratio (5.0%) indicated the lowest value for EC, and it was 3.98 ± 0.08 mS cm^{-1}. Furthermore, the treatments with 2.5% and 5.0% of 300 BC, 500 BC, sludge, and 5.0% compost exhibited significantly low EC values after the 4-month incubation period, indicating their equal efficacy in reducing the EC of

Table 3 Chemical and biochemical properties of organic amendments

	EC (1:5)	pH (1:5)	NO_3^-	PO_4^{3-}	CEC	SAR	ESP	TOC	Catalase activity	Phosphatase activity (acidic)	Phosphatase activity (alkali)
	dS cm^{-3}		mg kg^{-1}	mg kg^{-1}	cmol kg^{-1}		%	%	mL (0.05 mol L^{-1} $KMnO_4$) g^{-1} h^{-1}	µg (p-nitrophenol) g^{-1} h^{-1}	µg (p-nitrophenol) g^{-1} h^{-1}
300 BC	5.24 (0.02)	7.98 (0.05)	1.76 (0.02)	62.00 (0.29)	51.32 (0.76)	0.39 (0.02)	1.77 (0.03)	8.86 (0.07)	5.73 (0.02)	134.94 (3.15)	101.02 (3.53)
500 BC	9.20 (0.11)	10.82 (0.03)	2.10 (0.04)	80.99 (0.11)	52.24 (0.40)	0.92 (0.01)	2.25 (0.02)	6.64 (0.09)	1.73 (0.05)	96.77 (1.79)	54.08 (1.10)
700 BC	14.88 (0.03)	10.29 (0.02)	1.80 (0.02)	71.70 (0.14)	52.14 (0.42)	0.69 (0.02)	2.34 (0.02)	5.92 (0.06)	0.40 (0.06)	53.34 (2.00)	49.64 (2.50)
Compost	5.24 (0.06)	7.70 (0.03)	3.90 (0.02)	8.78 (0.10)	48.43 (0.28)	6.16 (0.02)	36.59 (0.02)	10.40 (0.20)	0.80 (0.03)	682.20 (3.70)	1587.50 (7.37)
Sludge	0.76 (0.02)	4.97 (0.06)	2.12 (0.02)	8.48 (0.07)	43.33 (0.91)	11.42 (0.06)	66.73 (0.07)	9.51 (0.04)	0.87 (0.03)	1895.37 (6.10)	1616.03 (6.50)

The value given for each parameter is the mean of three determinations, and the standard deviation (SD) for each value is mentioned in parenthesis

EC electrical conductivity, *CEC* cation exchange capacity, *SAR* sodium adsorption ratio, *ESP* exchangeable sodium percentage, *TOC* total organic carbon

acidic-salt affected soil. Organic amendments are known to be involved in lowering the EC of soils due to their enhanced salt adsorbing potential. Previous studies had also reported similar reductions in soil EC when different organic amendments were applied to reclaim the salt-affected soils (Tejada et al. 2006).

The variation of pH among different treatments with different ratios of organic amendments showed the same trend for both 1- and 4-month incubations (Fig. 2). Although, there was no substantial difference in pH observed between 1- and 4-month incubations. The amendment ratio is significantly involved ($p < 0.050$) in determining the pH of the acidic-salt affected soil except for the sludge-amended treatments. However, all the organic amendments increased the pH of acidic-salt affected soil proportionately with the increasing amount of amendment application. Further, the 5.0% amendment ratio of 700 BC and compost was equally effective for the increase of pH in acidic-salt affected soil by more than 40% and caused the pH to raise over 6 making a conducive condition for plant and soil microorganism growth.

The results of previous studies have shown the ability of biochar to raise soil pH about 30% compared to that of lime (Steiner et al. 2007; Glaser et al. 2002). However, the extent of the pH change in the soil is directly influenced by the application rates of biochar. The study of Sika and Hardie (2014) indicated the increases of soil pH in acidic soil (pH 5.14) up to pH 6.80, 7.34 and 8.42 with the application of biochar at 0.5%, 2.5% and 10% of respective ratios. However, the pH of biochar is primarily dependent on the feedstock type and the temperature used for the pyrolysis process (Agegnehu et al. 2017). Therefore, the three types of biochar and their amendment ratio used in this study influenced the variation of pH in acidic-salt affected soil, which is reflected in Table 3.

Figure 3 indicates the variation of soil nitrate levels after the addition of organic amendments into the examined acidic-salt affected soil at different ratios. Irrespective of the ratio applied, all the amendments increased the soil nitrate concentration above four folds over the control counterpart. However, the maximum increments of nitrate were reported by compost amended at 2.5% and 5.0% ratios. The highest nitrate concentration has resulted in 2.5% compost application (1.79 ± 0.08 mg kg^{-1}) over the 1-month incubation period while the maximum nitrate concentration observed in 5.0% compost (1.72 ± 0.02 mg kg^{-1}) after 4 months of incubation, although the difference between those values is not significant ($p = 0.226$). Moreover, 1 month and 4 months of incubation periods did not show a significant influence ($p > 0.050$) on the nitrate concentrations in acidic-salt affected soil.

The increased soil nitrate concentration after the application of organic amendment shows a direct relationship with the nitrate concentration presented in them (Table 3). The

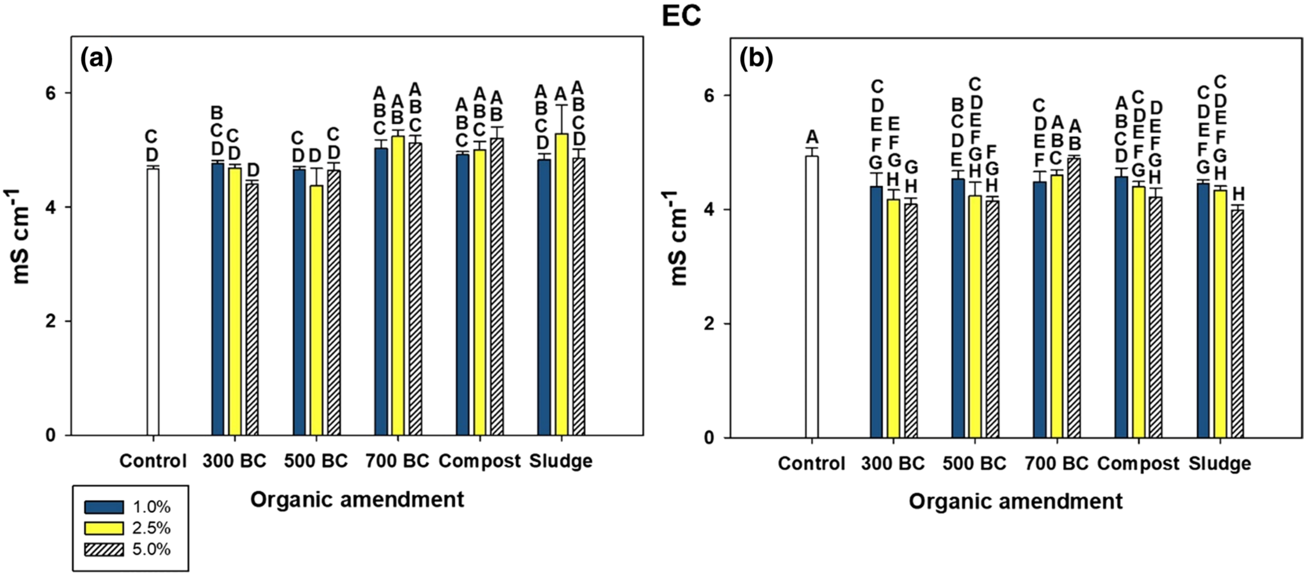

Fig. 1 Changes of electrical conductivity (EC) of acidic-salt affected soil after 1-month (**a**), and 4-month (**b**) incubations, with the addition of organic amendments at different ratios. The bars labeled with same letter indicate no statistical difference (Tukey method; $p > 0.05$)

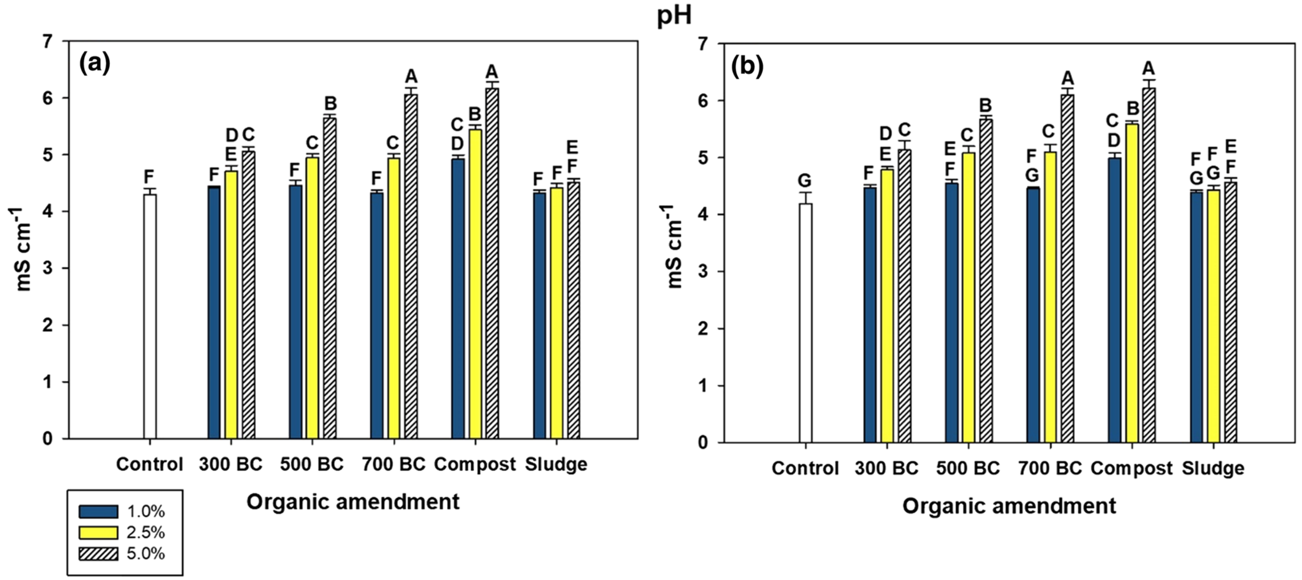

Fig. 2 The pH differences of acidic-salt affected soil in 1 month (**a**), and 4 months (**b**) after the application of different organic amendments with three different ratios. The bars labeled with same letter indicate no statistical difference (Tukey method; $p > 0.05$)

nitrate concentration of organic amendments increased with the order of 300 BC < 700 BC < 500 BC < sludge < compost and soil nitrate concentration followed the same order after the 4 months of incubation period of organic matter application (Fig. 3 b). Therefore, the mineralization of nitrogen compound associated with the organic amendments might be the reason for increased nitrate concentration in amended soil.

Similarly, the soil phosphate concentration in acidic-salt affected soil indicated a significant increment ($p < 0.050$) over the control as a result of the application of any type of organic amendment at all application rates (Fig. 4). After 1 month of incubation period, all the amendments with any ratio showed elevated soil phosphate concentration being approximately 1.5–2.3-fold higher than the corresponding control. However, soil phosphate concentration after 1 month

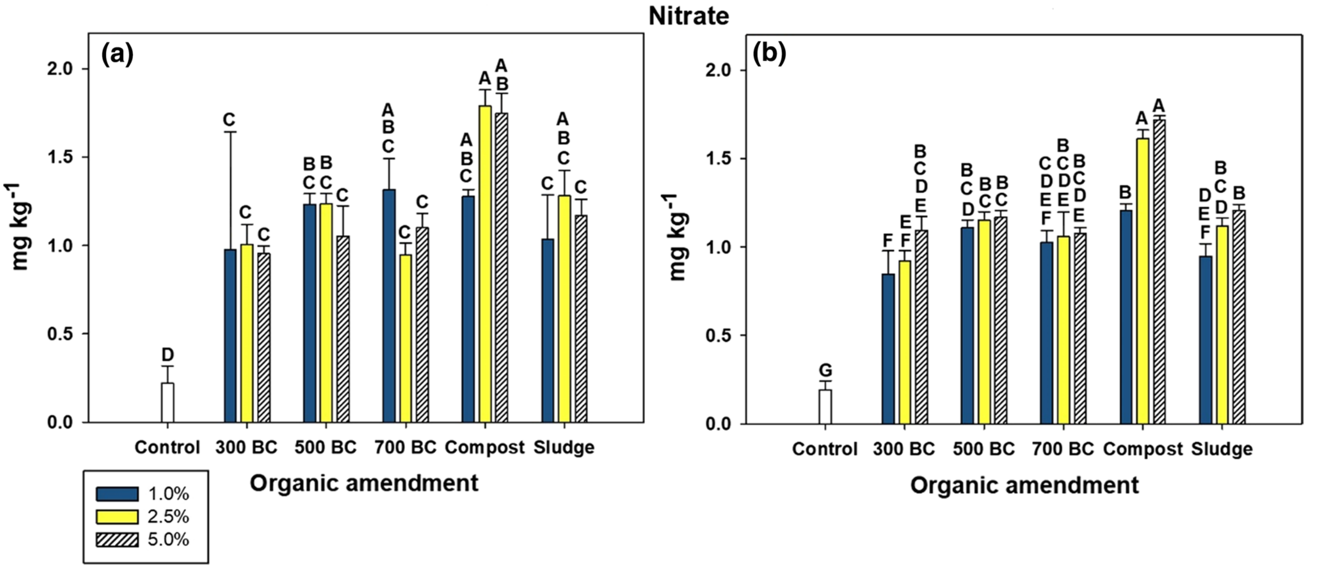

Fig. 3 The effect of organic amendments at different concentrations on nitrate concentration in acidic-salt affected soil after 1 month (**a**), and 4 months (**b**) of incubation period. The bars labeled with same letter indicate no statistical difference (Tukey method; $p > 0.05$)

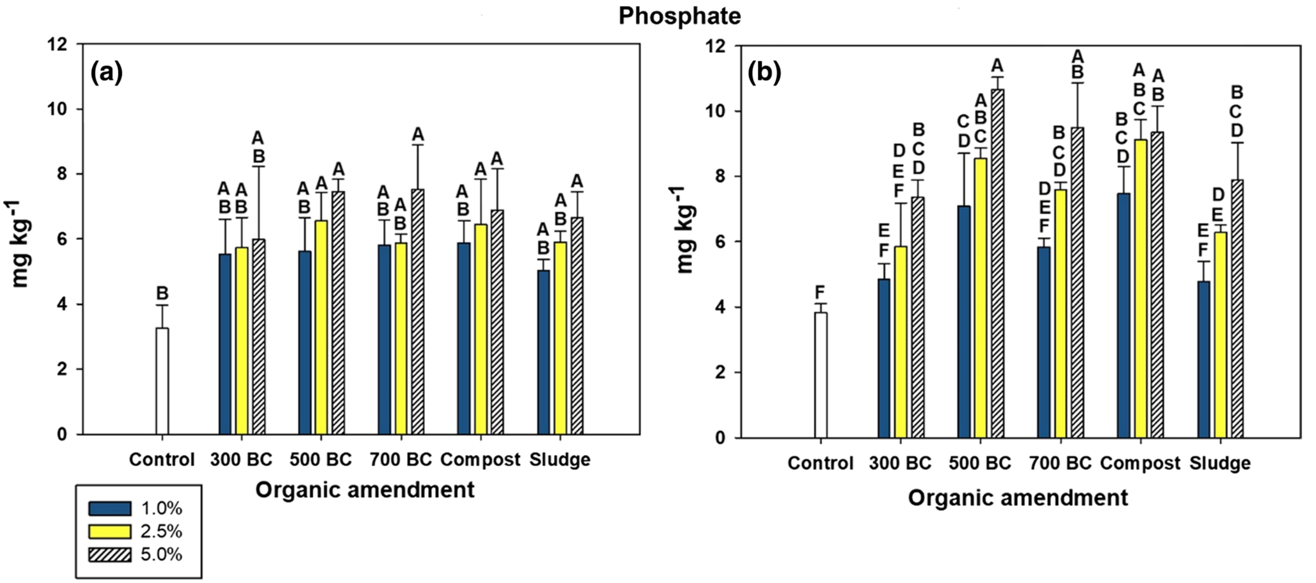

Fig. 4 The phosphate concentration of acidic-salt affected soil after 1 month (**a**), and 4 months (**b**) of incubation period with organic amendments at three different ratios. The bars labeled with same letter indicate no statistical difference (Tukey method; $p > 0.05$)

did not show a significant variation ($p > 0.050$) among different organic amendments or application ratio. After 4 months of incubation, soil phosphate concentration of all treatments with 2.5% and 5.0% of any of the amendment showed a considerable increment with reference to that of 1 month of incubation. Furthermore, the highest phosphate concentration reported after 4 months (i.e., 10.66 ± 0.33 mg kg^{-1}) in 5.0% of 500 BC application was significantly higher than the maximum phosphate concentration reported after 1 month (i.e., 7.53 ± 1.20 mg kg^{-1}) in 700 BC application at amendment ratio of 5.0% ($p = 0.012$). Organic amendments are known to contain phosphorous in organic and inorganic forms; however, inorganic phosphorous is the major form (Requejo and Eichler-Löbermann 2014). Mineralization of organic matter that introduced into the soil with amendment application by soil microorganisms could be attributed for the increased phosphate concentration in acidic-salt affected soil.

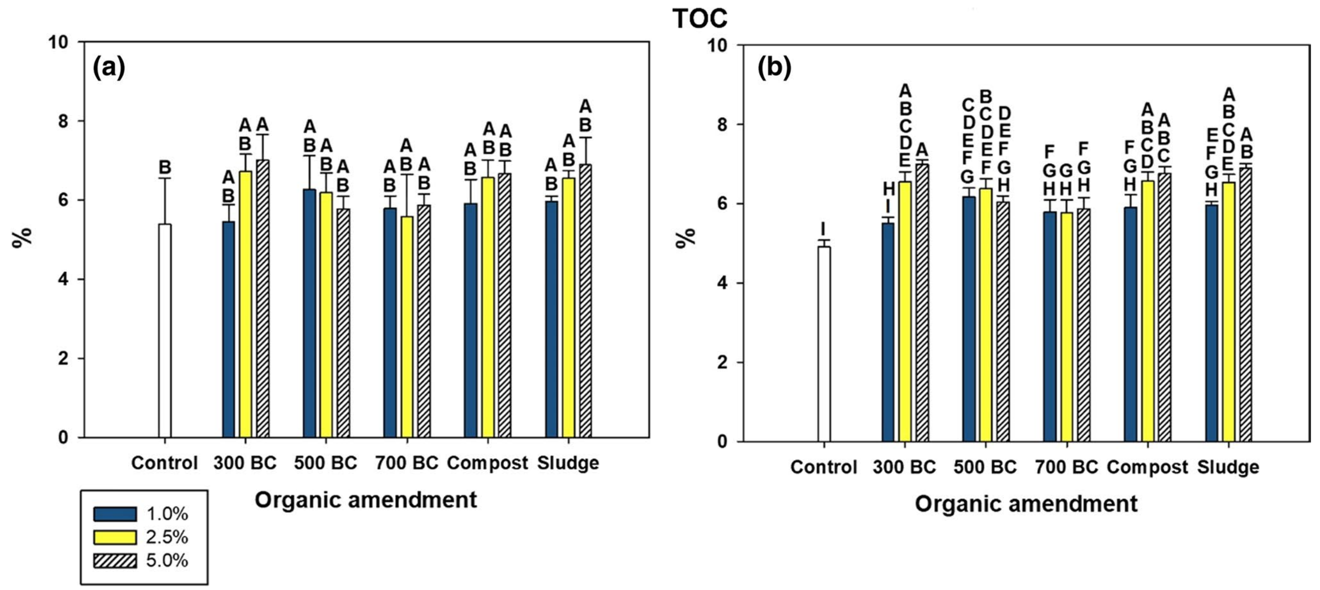

Fig. 5 Total organic carbon (TOC) percentage in acidic-salt affected soil incubated with organic amendments after 1 month (**a**), and 4 months (**b**) of incubation periods. The bars labeled with same letter indicate no statistical difference (Tukey method; $p > 0.05$)

Figure 5 represents the changes in soil total organic carbon percentage (TOC) after 1 and 4 months of incubation with the application of organic amendments. The 300 BC at 5.0% of amendment ratio caused the highest increment of TOC in acidic-salt affected soil, both after 1 month (7.01 ± 0.57 mg kg^{-1}) and 4 months of incubation (7.00 ± 0.11 mg kg^{-1}). Furthermore, in the 4 months of incubation, 2.5% and 5.0% of 300 BC, compost, and sludge showed a significantly higher increase in TOC in acidic-salt affected soil than other treatments.

Figure S1 shows the changes in cation exchange capacity (CEC) over the incubation periods of 1 and 4 months following the application of organic amendments with three different ratios. The CEC values after the first month of incubation did not show any significant variation among treatments with different organic amendments and the control (Figure S1a). However, after 4 months of incubation period, the CEC values in all the treatments improved significantly compared to the control ($p < 0.050$), being the highest in the treatment with the highest amendment ratio (i.e., 5.0%) of compost (49.20 ± 1.39 cmol kg^{-1}). The application of compost could increase the CEC of soil by 20%–70% of original CEC values (Lakhdar et al. 2009; Havlin et al. 2005). Furthermore, biochar application has confirmed its great potential for increasing of CEC values in soil (Novak and Busscher 2013).

Similar to the CEC, the sodium adsorption ratio (SAR) did not change significantly ($p > 0.050$) among all the treatments, including the control, after the first month of incubation (Figure S2a). Although, only the 2.5% and 5.0% of 700 BC amendment reduced the SAR significantly ($p < 0.050$) after 4 months of incubation compared to the control (Figure S2b). The lowest SAR (9.07 ± 0.47) was reported in 5.0% application ratio of 700 BC.

Figure S3 illustrates the variation in exchangeable sodium percentage (ESP) with the application of organic amendments. Application of organic amendment showed no significant effect ($p > 0.050$) on the change in ESP after the first month of incubation (Figure S3a). However, after the 4 months of incubation, ESP in the acidic-salt affected soil was reduced significantly in all the treatment with organic amendments compared to the control ($p < 0.050$) (Figure S3b). Maximum reduction of ESP was observed in 5.0% application of 700 BC (55.70 ± 1.90%); however, the same ratio (i.e., 5.0%) of 500 BC showed no statistical difference (Figure S3b).

3.2 Changes in soil enzymes

Catalase activity of soil is strongly linked with the respiration of soil aerobic microorganisms, soil fertility and organic matter content. It also acts as an indicator for redox potential of soil (Brzezińska et al. 2005; Guangming et al. 2017). Moreover, catalase is one of the enzymes showing the highest sensitivity to the changes in the environment, including the salinity changes (Guangming et al. 2017). Therefore, the evaluation of catalase activity provides a better indication of soil salinity changes. The changes in catalase activity in the soil subject to the organic amendments are presented in Figure S4. After the 1 month and 4 months of the incubation period, the catalase activity was reduced in all the treatments with organic amendments compared to the control, except in the treatments with sludge (Figure S4). Although the application of sludge at highest amendment ratio (i.e., 5.0%) caused the maximum increment of catalase activity, it is not significant when compared with the control set. The characterization data (Tables 1 and 3) revealed the catalase activity of sludge (0.87 mL (0.05 mol L^{-1} $KMnO_4$) g^{-1} h^{-1}) was approximately eight times lower than the original acidic-salt affected soils (6.86 mL (0.05 mol L^{-1} $KMnO_4$) g^{-1} h^{-1}). Therefore, an increase in catalase activity after sludge amendment might be attributed to the presence of a greater number of aerobic microorganisms in the sludge in their inactive forms, and the microbial catalase activity was subjected to change in the saline environment of the soil tested.

In contrast to the catalase activity, the maximum acid phosphatase activity was recorded in 5.0% of 500 BC amended acidic-salt affected soil, and 2.5% and 5.0% of compost amended acidic-salt affected soil, after 1 month and 4 months of incubation periods (Figure S5). Moreover, none of the amendment ratios of 700 BC and compost showed a significant change in acid phosphatase activity compared to the control ($p > 0.050$).

Alkaline phosphatase is the main enzyme responsible for the cycling of phosphorus in soil by the conversion of organic phosphorous into a mineral form (orthophosphate) that is available to the plants (Dick and Burns 2011). The activity of alkaline phosphatase in the soil provides a better indication of phosphorus mineralization, and thus the microbial activity of soil (Zhang et al. 2014). Figure 6 indicates the changes of alkaline phosphatase activity of acidic-salt affected soil following the application of different organic amendments. After 1 month of the incubation period, any of the treatment with organic amendment did not show any significant increase ($p > 0.050$) of the alkaline phosphatase activity in acidic-salt affected soil compared to the control (Fig. 6a). However, after the 4 months of incubation period, all the amendment ratios of 300 BC, 500 BC and compost significantly increased the soil alkaline phosphatase activity ($p < 0.050$); while, only the highest amendment ratio (i.e., 5.0%) of 700 BC and sludge showed a significant increment in this enzyme activity compared to the control (Fig. 6b). The study of Guangming et al. (2017) suggested the enhanced alkaline phosphatase activity in salt-affected soil after application of organic fertilizers. Improved microbial diversity and their activities caused by increased substrate availability and nutrients provided by organic matter could be the reason for enhanced alkaline phosphatase activity that observed after the application of organic matter. Furthermore, increased C/N ratio caused by organic matter application might have involved for the increased enzymatic activities in acidic-salt affected soil as C/N ratio plays a vital role for microbial decomposition of organic matter which increase enzymatic activities of microorganisms (Tejada et al. 2006).

3.3 Overall impact of organic amendments and amendment ratios on the reclamation of acidic-salt affected soil

When considering the results for 1 month and 4 months of incubations, a clear relationship was observed in values obtained for the evaluated parameters and the amendment

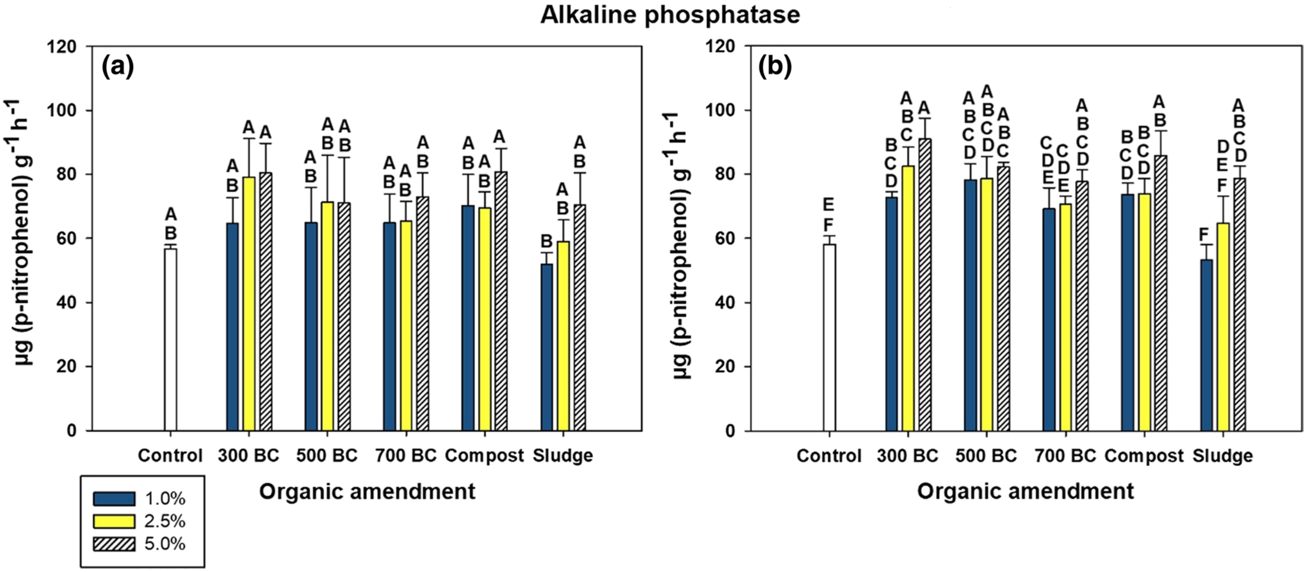

Fig. 6 Impact of different organic amendments and application ratios on soil alkaline phosphatase activity after 1 month (**a**), and four months (**b**) of incubation period. The bars labeled with same letter indicate no statistical difference (Tukey method; $p > 0.05$)

ratios (i.e., 1.0%, 2.5% and 5.0%) for all amendment types (300 BC, 500 BC, 700 BC, compost and sludge). For most of the parameters examined, the 5.0% amendment ratio showed a greater percentage of positive changes than 1.0% and 2.5% (Figs. 1, 2, 3, 4, 5, 6 and S1–S5). Therefore, the 5.0% amendment ratio can be considered as the most effective amendment ratio for reclamation of acidic-salt affected soils.

However, the results of this study showed variations in the effectiveness and efficiencies of different organic amendments in bringing about changes in different chemical and biochemical parameters evaluated for the acidic-salt affected soil. Therefore, all the amendments at 5.0% application ratio, after 4 months of incubation period were selected as the optimum under the tested conditions of study, for the reclamation of the examined acidic-salt affected soil based on their sustained overall performance in ameliorating chemical and biochemical profile of the soil (Fig. 7). To do so, a specific number from one to five was assigned for each organic amendment used at 5.0% application ratio according to its performance in changing each parameter. For EC, SAR, and ESP, the least value was allocated for the highest rank, and for all the other parameters, the highest rank was assigned for the maximum value.

The cumulative value of rank shows 500 BC was the most effective organic amendment for the reclamation of acidic-salt affected soil, scoring 38 (Fig. 7). Therefore, 500 BC possesses many favorable characteristics that were effectively involved in the reclamation of acidic-salt affected soil. However, compost obtained a score of 37, making it the second most effective amendment. The overall order of the performance of the 5.0% organic amendments in the reclamation of the acidic-salt affected soil tested is, 700 BC < Sludge < 300 BC < Compost < 500 BC (Fig. 7).

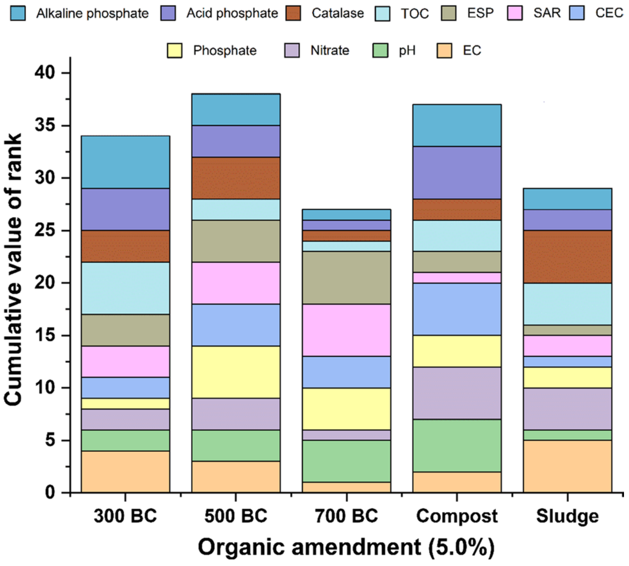

Fig. 7 Overall comparison of potentials among the organic amendments at a 5.0% application ratio for the reclamation of acidic-salt affected soil after four months of the incubation period

Among the five types of organic amendments used, 300 BC was proved effective in accomplishing the highest increment in alkaline phosphatase activity and TOC content, second most increase for acid phosphatase, and second most reduction in EC. However, the changes made by 300 BC in pH, nitrate, phosphate, and CEC were relatively low. The alkaline phosphatase activity is strongly correlated with the soil organic matter content (Guangming et al. 2017). Therefore, the highest alkaline phosphatase activity reported in the soil amended with 300 BC might have resulted from the highest TOC value associated with it among all the other amendments used. In contrast, the 700 BC reported the highest performance in decreasing SAR and ESP but offered the lowest increments in TOC, catalase, acid phosphatase, and alkaline phosphatase activities and the lowest reduction in EC. The SAR reflects the concentration of Na^+ relative to the square root of the average concentrations of Mg^{2+} and Ca^{2+} in soil solution. Application of organic amendment is well known to increase Mg^{2+} and Ca^{2+} in soil solution at marked concentrations (Chaganti et al. 2015). Therefore, 700 BC probably introduced a strikingly high amount of Mg^{2+} and Ca^{2+} ions into the acidic-salt affected soil, which might be the reason for the reduction of the SAR. Moreover, the high reduction of ESP in acidic-salt affected soil might have resulted from the release of Ca^{2+} into the soil from 700 BC and dissolution of calcite in acidic-salt affected soil induced by the addition of 700 BC (Chaganti et al. 2015). Increasing Ca^{2+} concentration in soil enhanced the rate of Na^+ and Ca^{2+} exchange amongst the exchangeable sites of soil colloids and soil solution leading to ESP reduction in acidic-salt affected soil. Furthermore, the high pH value attributed to 700 BC (i.e., pH = 10.29) is the reason for the rise in the pH value of acidic-salt affected soil to a great extent.

Therefore, 300 BC is a promising amendment suitable for the enhancement of soil microbial activities and increase in TOC; whereas, 700 BC enabled the highest reduction in soil acidity and salinity among all three types of biochar used. However, the current results indicate that 500 BC is the ideal candidate among three types of biochars to reclaim the acidic-salt affected soil examined due to its intermediate nature of properties and abilities to reclaim soil concurrently affected with both salinity and acidity (Fig. 7).

Many studies have reported the potential of biochar to enhance soil properties and control soil salinity for improving the growth performance of crop plants as well (Akhtar et al. 2015; Hammer et al. 2015; Najeeb et al. 2017). Biochar can provide a good source for mineral nutrients such as K^+, Mg^{2+}, and Ca^{2+} (Huang et al. 2019; Chaganti and Crohn 2015). The release of these cations from biochar causes displacement of Na^+ ions associated with exchangeable sites of acidic-salt affected soil colloids and facilitates further leaching of Na^+. As a consequence, with the reduction of soil salinity, soil qualities and stability become enhanced (Hammer et al. 2015; Chaganti and Crohn 2015; Lashari et al. 2013). Furthermore, biochar has a great influence on altering microbial diversity, composition, and biomass in soil (Lehmann et al. 2011; Thies et al. 2015). The porous structure and great surface area of biochar, together with high capacity to absorb and retain soluble inorganic nutrients, make an optimal condition for the growth and colonization of microorganisms (Thies and Rillig 2012). Also, the buffering capacity of biochar maintains the pH of soil that sustains microbial diversity and abundance since they exhibit a strong correlation with ambient soil pH (Rousk et al. 2010). Therefore, biochar enhanced the enzymatic activities of soil, including acid and alkaline phosphatase, which indicate increments in the soil microbial population. Many studies including Abujabhah et al. (2016) provide supporting evidence for improved microbial abundance and activities after exogenous input of biochar into the soil.

However, among all amendments, sludge has shown the highest reduction in EC and increment in catalase activity, but it made less pH alteration. Sludge is derived from sewage which is naturally enriched in diverse microorganisms, and they tend to concentrate more in sludge (Straub et al. 1993). As a result, the application of sludge can increase the soil microbial population in the amended soil. Therefore, the treatment with sludge increased the catalase activity in the acidic-salt affected soil, indicating enhanced activity of aerobic microorganisms. However, the sludge used in the current experiment had considerably low pH value (i.e., pH = 4.97) (Table 3), which was slightly higher than the native pH of the acidic-salt affected soil (i.e., pH = 4.04) (Table 1). Therefore, the involvement of sludge in increasing the pH of acidic-salt affected soil was not significant.

Moreover, the highest values for available nitrate, pH, CEC, and acid phosphatase activities were recorded in the compost-treated sets, which also established the second-highest potential for improvement of chemical and biochemical properties of acidic-salt affected soil (Fig. 7). The amendments with raised CEC values have high potential to adsorb soluble salts that are involved in reducing the salinity of soil (Mahdy 2011). Therefore, the high CEC value of compost applied in the current study caused the lowering of soil salinity to a great extent, which might have contributed much to the improvement of other soil attributes as well. Therefore, the application of organic matters, especially the biochar and compost offer immense potential for enhancing soil biological activities, available macro-nutrient contents, and, ultimately, a reduction in salinity.

4 Conclusions

Different amendments at varied application ratios and incubation periods imparted a differential impacted the chemical and biochemical properties of acidic-salt affected soil differently, which bear clear implications for their relative reclamation efficiency. The increasing ratio of amendment application facilitated favorable alterations in the chemical and biochemical properties of the soil tested, and the 5.0% amendment ratio of all organic amendments resulted in desirable improvement in most of the properties of the tested acidic-salt affected soil. Further, the 4 months of incubation time sustained amelioration in soil properties better than the 1 month of the incubation period. However, 500 BC at its maximum (i.e., 5.0%) application rate showed the highest overall performance in reclaiming acidic-salt affected soil by improving most of the soil properties. Above all, the overall reclamation potentials of organic amendments were registered in the following ascending order: 700 BC < Sludge < 300 BC < Compost < 500 BC.

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